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EQUILIBRIUM THEORY OF EROSIONAL SLOPES APPROACHED BY FREQUENCY DISTRIBUTION ANALYSIS

ARTHUR N. STRAHLER

PART I

ABSTRACT. In the quantitative analysis of erosional landforms one of several form-elements requiring measurement is slope angle of valley walls. Field sampling of slope angles in several mature regions differing widely in lithology, relief, vegetation, climate and soils has yielded data suited to frequency distribution analysis. Determination of means, estimated standard deviations, skewness and normal distribution fitness have provided a quantitative basis for slope description and significance tests.

Distributions show a wide range of means, but are symmetrical and have low dispersions. This is taken as evidence of a prevailing condition of form-equilibrium accompanying a steady state in an open system of erosion and transportation. Comparison of valley-wall slopes with adjacent channel gradients reveals a strong, positive correlation, indicating a high degree of adjustment among component parts of a drainage system.

Tests for significance of differences in slope means of three localities in the Verdugo and San Rafael Hills showed that (1) factors other than lithology exert major control over observed differences in slope angles, (2) directional exposure has no significant effect upon slope angles, and (3) slopes left to weathering, sheet wash and creep without stream corrasion at the base have reclined in angle.

INTRODUCTION

A LARGE proportion of the earth's land surface is composed of erosional landforms produced by channel erosion in drainage networks operating in conjunction with raindrop and sheet-runoff erosion and mass gravity wasting on the contributing slopes. In a mature stage of development the landscape consists of an intricate combination of channels, slopes and divides. Although the same unit form is not exactly repeated throughout this type of topography, an observer cannot fail to recognize that the forms are approximately the same throughout an area having a uniform lithology, geologic history, climate, soil and vegetation. Examples may be cited from

the intricately dissected California Coast Ranges; from the monotonously repetitious landforms of the dissected Appalachian Plateaus; or from the marl hills of badlands in northern Arizona.

Although our understanding of erosional landforms is still in a stage of generalized verbal description, some attempts have been made to separate the various elements of form from the topographic complex. Robert E. Horton (1945) has analyzed drainage network composition in terms of drainage density, stream frequency, stream number, stream order, and bifurcation and length ratio.

Despite the apparent complexity of a quantitative analysis, it is possible to define and measure the various form-elements which comprise a fluvially dissected landscape. This is the first step in an over-all investigation aimed at relating quantitatively the influence of causative factors to form characteristics. Slope is one of the form-elements and is the principal topic of this paper.

In considering quantitatively the element of slope in an erosional landmass it is possible to measure and compare (1) forms of slope profiles as mathematical curves, (2) lengths of slopes from divide to base (scale-aspect of the topography), and (3) angles of slope with respect to the horizontal (gradient-aspect of the topography). Because the principal concern of this paper is with the third measure, the first two are discussed only briefly.

In a maturely dissected region of homogeneous rock the common slope profile, when taken along an orthogonal line with respect to the contours, tends to be straight in its middle and lower parts (fig. 1). At the upper end the profile becomes convex-up, passing into the rounded divide. Where streams are effectively corrading a channel at the slope base the profile continues to the base as a nearly straight line (plate 1). Concavity at the base, so commonly shown in elementary textbooks, seems to occur only where accumulations of slope-wash or slide-rock lie at the slope base, or where structural control is present. Straightness of profile has been noted by Lawson (1933) in the California Coast Ranges and by the writer in that same province as well as in many other places in the United States. It may be seen in the bold mountains of the Great Smoky mass as well as in small-scale badland forms in

weak clays. The common illusion of generally concave-up slopes comes from viewing profiles of lateral spurs or other lines which are not true orthogonals.

Length of slope, a function of the general scale of the drainage network, is related to the infiltration capacity and resistivity of the surface to corrasion and other factors and is therefore left to be treated elsewhere in quantitative considerations of drainage density and its variations.

Slope steepness is a particular form-element which lends itself to analysis by the standard methods of frequency distribution statistics. Even the most casual geological observer has noted that slope steepness varies widely from one region to another, but that it seems fairly constant within the limits of a small area of uniform relief and rock composition. Thus slopes may be said to reflect a steady state in the rate of removal of debris and the rate of supply of debris. Slopes seem to tend toward a constant angle which is related to the particular conditions of

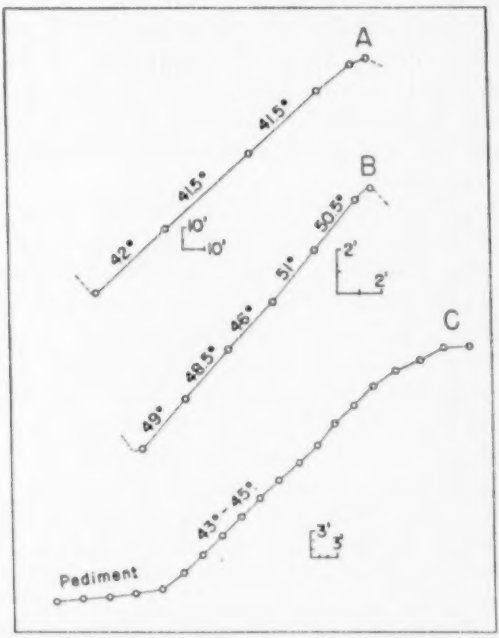

Fig. 1. Profiles of three valley-wall slopes surveyed in the field. (A) Verdugo Hills, Los Angeles Co., California. (B) Dissected clay dump, Perth Amboy, N. J. (C) Petrified Forest National Monument, Ariz.

soil, bedrock, vegetation, climate and relief, and which is integrally adjusted with conditions of channel gradient and stream regimen.

The concept of equilibrium has long been applied to graded streams and their associated slopes but the nature of this equilibrium and its basic similarities with other systems of equilibrium in nature seem not to have been fully examined. A graded drainage system is perhaps best described as an open system in a steady state (von Bertalanffy, 1950) which differs from a closed system in equilibrium in that the open system has import and export of components. An example of an open system in physics might be the flow of heat through a conducting solid. When a steady state is attained the temperature at a given point remains constant while the flow of heat continues. In biology the metabolism of a stable organism is best described as operating in a steady state requiring an exchange of materials with the environment and a continuous building up and breaking down of materials within the organism. Open systems consume energy to maintain a steady state, whereas closed systems require no energy for the maintenance of equilibrium. Still another property of the open system is that a disturbance in the flow of materials or energy will cause a readjustment to take place until a time-independent steady state is reestablished.

In a graded drainage system the steady state manifests itself in the development of certain topographic form characteristics which achieve a time-independent condition. (The forms may be described as "equilibrium forms".) Erosional and transportational processes meanwhile produce a steady flow (averaged over periods of years or tens of years) of water and waste from and through the landform system. Potential energy of position is transformed into kinetic energy of water and debris movement or heat. Over the long span of the erosion cycle continual readjustment of the components in the steady state is required as relief lowers and available energy diminishes. The forms will likewise show a slow evolution.

Applied to erosion processes and forms, the concept of the steady state in an open system focuses attention upon the relationships between dynamics and morphology. With this concept in mind, the first steps in measurement and description of slope forms typical of the steady state can be undertaken.

ACKNOWLEDGMENTS

The writer wishes to thank Dr. Howard Levene of the Department of Mathematical Statistics, Columbia University, for critically reading the paper and suggesting improvements. Field work in 1947 was supported by the Kemp Memorial Fund of Columbia University and in 1948 and 1949 by Grant 525-48 from the Penrose Bequest of the Geological Society of America.

GENERAL PRINCIPLES

Method of Obtaining Field Data.—Slope sampling requires decision as to (1) type of data wanted, (2) rules of sampling to be followed in the field, and (3) size of sample required.

In the present investigation it was required that only the steepest part of a profile line of slope be measured; furthermore, that the profile line must follow the true down-slope line from divide to base of slope (the orthogonal line with respect to contours). Following this rule the observer is prevented from having a choice as to what part of a profile to select; the use of apparent, rather than true maximum slopes is avoided. Thus any two or more observers should obtain the same angle of slope from any given point in the field, subject only to errors of measurement.

There is a more important and fundamental reason for using the steepest part of a slope profile. It is postulated that in mature topography a slope is the morphological manifestation of a steady state in which the forces which remove material are so adjusted to the resistive properties of the surface as to provide a steady supply of debris to the streams. The steepest part of a slope will then reflect the maximum angle which can be maintained, and is an indicator of the relative effectiveness of the opposed forces in the equilibrium relationship. Because the slope at its upper part declines in angle to become horizontal on the divide, angles less than the maximum have little significance and their use would bring in a broad element of subjective sampling. As the ultimate aim in geomorphology must be a dynamic understanding, it is essential that those form-elements be measured which can be most easily related to causative forces.

In field sampling, only valley-wall slopes leading down into the sides of a channel were used. Slopes leading into the ex-

treme head of a ravine were not used because of the element of strong convergence present. Slopes down the axes of spurs, where lateral divides descend to a main stream, were not used because these are not true orthogonals. Drainage basins of the first and second, sometimes third orders were used. Avoidance of higher order master streams eliminates the reading of slopes abnormally steepened by strong lateral corrasion of a large stream.

Within each area an attempt was made to take slope readings at approximately equally spaced positions along the contour. In the case of fine-textured badlands these were spaced only 5 to 10 feet apart, or about one-fourth to one-half of the prevailing slope length. In medium-textured topography with slope lengths of 100 to 300 feet the spacing was 100 to 150 feet. This raises the question of how close together any two profile lines can lie before they can be considered as one statistical item in a frequency distribution, rather than as two separate items. The problem exists because the sampling is from a continuous surface which varies in orientation from place to place, rather than from a population of discrete pieces or objects, as for example, a clastic sediment. Because all movement of detritus on a slope takes place along the true down-slope profile lines, one would not have to move far laterally along a slope to encounter relatively independent threads of debris movement. With the spacing used by the writer successive profiles were separated by what seemed to be a relatively broad belt of slope, equivalent to one-half to one-third of the slope length itself; hence no mutual interference seemed likely.

Slope angles were read to the nearest degree or half degree with Abney hand level or Brunton compass. A class interval of 2° or more is desirable in the frequency distribution analysis, because the range of error for any item is almost a half degree. On mountain or hill slopes the steepest down-slope line was determined by rolling boulders or pebbles down-slope, or by selecting the maximum of a range of readings aimed down-slope through a lateral arc. When a two-man team is used, each man takes a position on the slope line. The instrument man then reads the slope to the eye-level of his partner. In this way minor ground irregularities and brush can be overcome. When one is working alone, he can put up a perpendicular rod with the eye-level marked, or make a mark at eye-level on a

convenient tree trunk or bush. Slopes were read over lengths equivalent to one-fourth or one-fifth of the slope length so as to avoid minor irregularities made by boulders or clumps of vegetation. As most slopes are relatively straight or steepen toward the base the measurement is taken near the base. Some slopes have a basal concavity due to local accumulations of slopewash or talus; the slope is then read above the zone of accumulation. In the case of small-scale badlands a 3-foot board was laid on the slope and the measurement taken as with dip of a bedding plane.

It is desirable to read the azimuth of each slope measurement so as to permit study of the effects of direction of exposure on slope angle. Readings should be located on the field map by a station number corresponding to the notebook record. This permits statistical analysis between individual basins or groups of basins.

Sample sizes taken by the writer ranged from 20 to 200 readings. Subsequent statistical analysis has shown that a sample of 50 slopes is adequate to reveal the characteristics of the distribution in a homogeneous region of 6 to 12 first-order drainage basins; while a sample of 25 will closely fix the mean.

The use of topographic maps as sources of slope data has been investigated and tests run between field and map readings of the same slopes. The statistical analysis of this procedure is treated in a later section of this paper. Regarding collection of data from maps the following conclusions have been reached: Maps on a scale of 1:24,000 or 1:25,000 published by the U. S. Geological Survey and the Army Map Service in recent years will give reasonably accurate results where topography is coarse-textured and the relief strong. These maps are prepared by photogrammetric methods and comply with National Standard map accuracy requirements. It was found that maps of a scale of 1:31,680 in Los Angeles County are unsuited to slope sampling because the topographic texture is too fine for the map scale and contour interval; *i.e.*, slopes are too short to be represented accurately under the cartographic conditions. Maps of the scale 1:62,500 are generally beyond the limits of reasonable accuracy and should be entirely avoided for slope sampling.

General Characteristics of Slope Frequency Distributions.— The methods of slope sampling described above were applied

to several areas differing widely in lithology, soil, relief, vegetation, and climate in order to obtain some idea of the range of characteristics present and the degree of homogeneity within each area. Figure 2 shows several histograms drawn on a common abscissa to show comparative positions on the slope scale 0° to 90°. For each distribution the following measures are given:

N Number of items in the sample.

$\bar{X}$ Arithmetic mean.

s Estimated standard deviation.

Cumulative frequency percentage distributions for the same samples are shown in figure 3. Both step-graphs, showing individual classes, and smoothed curves are shown.

With regard to general distribution properties, two points are especially noteworthy: (1) Dispersions are low, considering the range of angle possible, giving evidence of a high degree of homogeneity in the populations sampled. (2) Distributions are generally symmetrical, the principal exception being sample D. Inasmuch as sampling was carried out according to previously set rules and no readings were discarded

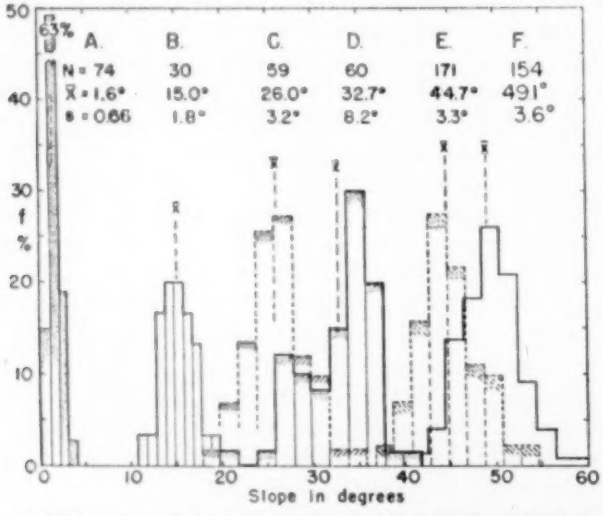

Fig. 2. Histograms of six slope frequency distributions. (A) Steenvoorde, France, (B) Rose Well gravels, Arizona, (C) Bernalillo, N. M., Santa Fe formation, (D) Hunter-Shandaken area, Catskill Mts., N. Y., (E) Kline Canyon area, Verdugo Hills, Calif., (F) Dissected clay fill, Perth Amboy, N. J. All data except (A) from field readings.

arbitrarily, either during the field sampling or during the processing of the data, the low dispersions and symmetry are interpreted as an indication that within a given small region where conditions of lithology, climate, soil, vegetation and relief are uniform, slopes tend to approach a certain equilibrium angle, appropriate to those controlling factors.

Slope Distributions and the Normal Curve of Error.—The problem of whether the distribution of maximum slopes in a selected region follows the normal curve of error was considered worthy of analysis in view of the possibility that the distribution is inherently skewed and is better represented by a logarithmic-normal curve, or some other variety of normal curve, such as one in which the abscissa is on a scale of tangents or log-tangents.

Three methods were used in analyzing the form of the distributions: (1) A plot on arithmetic probability paper. (2) A fitted normal curve and χ^2 test of goodness of fit. (3) Determination of significant skewness and kurtosis based on the third and fourth moments of the distribution.

A rough test of normal distribution may be had by plotting cumulative percentage frequencies on arithmetic probability paper. This paper is constructed to show the normal curve of

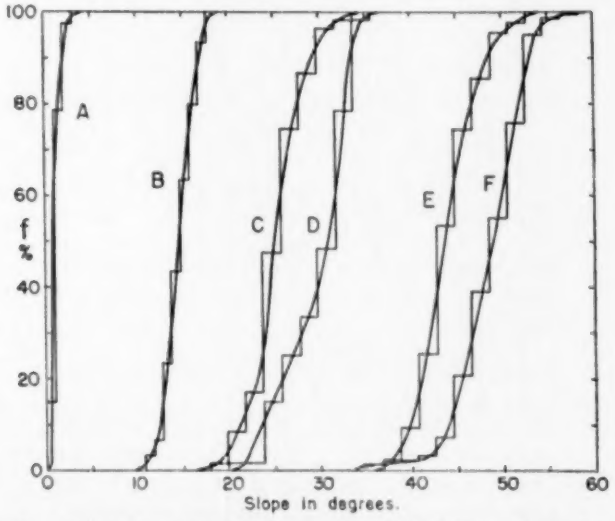

Fig. 3. Cumulative percentage frequency distributions. Same data as in figure 2.

error (cumulative) as a straight line. If the distribution appears reasonably straight one can proceed to fit a normal curve to the data. An additional feature of the cumulative curve on probability paper is that the slope is proportional to dispersion, hence the differences in dispersions between two normal distributions can be noted at a glance.

Figure 4 shows the data of figure 3 plotted on arithmetic probability paper. End classes containing only one item have been combined to compensate for the influence of scarcity. With the exception of sample D and the lower tail of sample F a reasonable straightness prevails, suggesting that the distributions are well described by normal curves, which may now be fitted to the data.

Fitting of the normal curve to the slope data of sample C, an area of dissected Santa Fe formation near Bernalillo, New Mexico, is illustrated in figure 5.

Goodness of fit has been determined by use of a χ^2 test in which theoretical frequencies and observed frequencies are compared as follows: (Croxton and Cowden, 1946, p. 286)

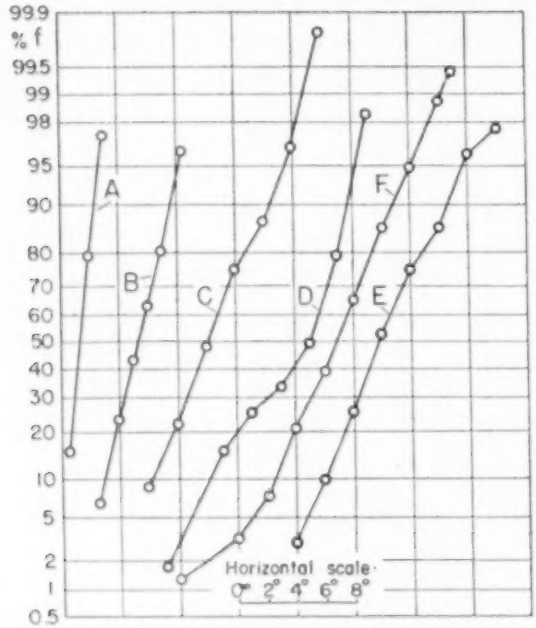

Fig. 4. Cumulative percentage frequency distributions on arithmetic probability paper. Same data as figures 2 and 3.

$$\chi^2 = \Sigma \frac{(f - f_e)^2}{f_e} = 0.631$$ where

f = observed frequency

f_e = expected frequency

The value n, representing the number of degrees of freedom, is obtained by subtracting the three degrees of freedom lost in the curve-fitting process from the original number of classes, seven, and is therefore equal to four. By consulting a prepared table we find for these values of χ^2 and n a probability, P, of approximately 0.97. Thus a normal curve of error is an excellent description of the distribution and, if the distribution is in fact normal, we should expect to find this good a fit or better in only 6 times out of one hundred such samples because of chance variations due to sampling only.

Tests of significant skewness and kurtosis were carried out on the raw data of three frequency distributions of slopes in the Verdugo and San Rafael Hills, Los Angeles County, California[1].

The purpose of the investigation was to determine if the various amounts of skewness and kurtosis visible in the three distributions are of such an order as to be commonly ob-

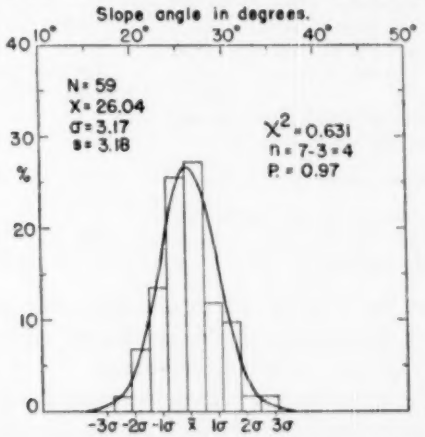

Fig. 5. Normal curve of error fitted to a frequency distribution of slope angles from the dissected Santa Fe formation near Bernalillo, New Mexico. Slopes measured in field.

[1] The analysis was carried out under the direction of Mr. Richard Ostheimer, Instructor in Statistics, Columbia University. Moments were computed from the raw data in order to remove possible influences of grouping.

tained by chance variations in sampling of a normal population, or whether they are significant of actual departures from normal in the population (fig. 6).

Skewness was determined from the value of β_1, a measure of skewness based upon the third moment of the frequency distribution:

$$\beta_1 = \frac{N\ (\Sigma x^3)^2}{(\Sigma x^2)^3}$$

Table 1 shows the results and conclusions for samples A, B, and C of figure 6. Samples B and C showed no significant skewness; sample A is doubtful of interpretation. Kurtosis was determined by the value of β_2, a measure of kurtosis based upon the fourth moment of the frequency distribution:

$$\beta_2 = \frac{N\ \Sigma x^4}{(\Sigma x^2)^2}$$

TABLE 1

Summary of analysis of skewness in three sample slope frequency distributions.

DETERMINATIONS MADE	Area A	Area B	Area C
β_1 (Distribution symmetrical when β_1 is 0; Right skewness when β_1 is +; left skewness when β_1 is −.)	+0.153	−0.005	−0.103
Probability of sample β_1 at least this large, if β_1 of universe is 0.	0.02 to 0.10	>0.10	>0.10
g_1 (Normally distributed measure of skewness. Symmetry when $g_1 = 0$.)	0.394	0.070	0.340
$\frac{g_1}{\sigma_{g_1}}\left(\frac{x}{\sigma}\text{ of a normal curve}\right)$	2.12	0.27	0.75
Probability of sample g_1 at least this large if g_1 of universe is 0.	0.02	0.39	0.23
Is the skewness significant?	?	No	No

Table 2 shows the results and conclusions for samples A, B and C. None of the samples shows significant kurtosis although the probability shows a considerable range.

The general conclusion which may be stated from the analysis of β_1 and β_2 is as follows: There is no reason to doubt that frequencies of each of the three areas are normally distributed. A possible exception is area A, in which the sample has right skewness, but the skewness is of questionable significance.

Law of Constancy of Slopes.—The tendency of slopes to group closely about a mean value may be taken as an expression of a morphologic law relating slope to other form factors. This

law may be stated as follows: Within an area of essentially uniform lithology, soils, vegetation, climate and stage of development, maximum slope angles tend to be normally distributed with low dispersion about a mean value determined by the combined factors of drainage density, relief and slope-profile curvature.

TABLE 2

Summary of analysis of kurtosis in three sample slope frequency distributions.

DETERMINATIONS MADE	Area A	Area B	Area C
β_2 (Distribution normal, mesokurtic, when $\beta_2=3.0$. Leptokurtic, or peaked, when $\beta_2>3$. Platykurtic, or flattened, when $\beta_2<3$.)	2.992	3.707	2.381
Probability of sample β_2 differing by at least this much from a population β_2 of 3.0	0.05	0.05	0.05
g_2 (Normally distributed measure of kurtosis. Mesokurtic when $g_2=0$.)	0.027	0.819	0.485
$\frac{g_2}{\sigma_{g_2}}\left(\frac{x}{\sigma}\text{ of a normal curve}\right)$	0.07	1.62	0.55
Probability of sample g_2 at least this large, if g_2 of universe is 0.	0.47	0.05	0.29
Is there significant departure from normal, mesokurtic form?	No	No	No

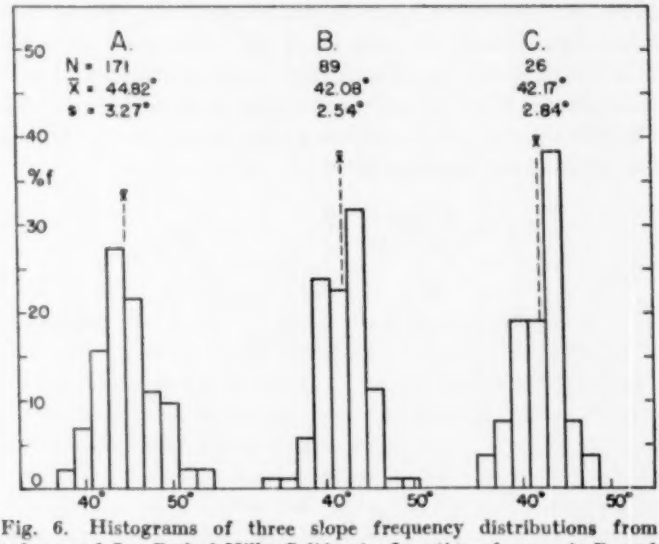

Fig. 6. Histograms of three slope frequency distributions from the Verdugo and San Rafael Hills, California. Location of areas A, B, and C is shown in figure 10. See tables 1, 2, 3, 4, 5, and 6 for summaries of data analysis.

If drainage density (Horton, 1945, p. 248),

$$D_d = \frac{\Sigma L}{A}$$ where ΣL = sum of stream lengths (projected onto a horizontal plane)
A = area.

then the mean horizontal distance from divide to channel is roughly one-half of the reciprocal of drainage density:

$$H = \frac{1}{2D_d}$$ where H = horizontal distance from stream to divide.

Now, if the spacing of streams is uniform throughout and the length of contributing slopes is similarly uniform, slope steepness can vary only as relief or profile curvature are varied (fig. 7).

Given two areas of the same drainage density, the area having the lower relief must have lower slopes, assuming profile curvature characteristics to be similar (fig. 7A). Given two areas of similar relief, but of different drainage density, slope must be less steep where drainage density is less (fig. 7B). If divides are broadly convex and only the basal fraction of the slope is straight, a steeper maximum angle is required than in a region of narrow divides and long, straight slopes, even though relief and drainage density are the same in both areas (fig. 7C). Because divide curvature is a factor readily influenced by stage of development or by structural conditions, it can be minimized only by the use of mature areas which behave as if lithology and structure were homogeneous.

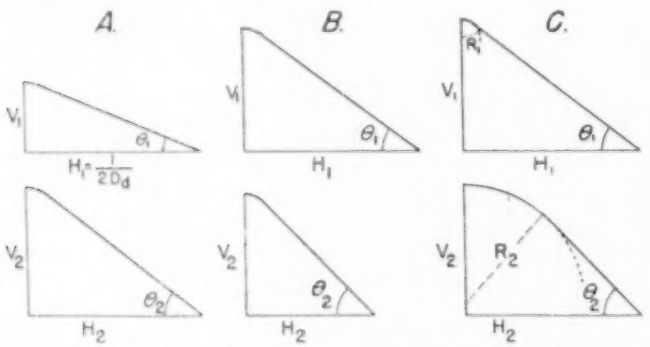

Fig. 7. Relationship of relief (V), slope (θ) and horizontal distance between divide and stream (H). Radius of divide curvature, R, is a variable diagram *C*.

Slope is thus seen to be proportional to the ratio between relief and one-half of the reciprocal of drainage density, assuming constant profile curvature characteristics. From figure 1 it is apparent that profiles are similar in form for both the fine-textured badlands on dissected clay fill near Perth Amboy (A) and for the medium-textured Verdugo Hills in Los Angeles County (B). Both have long, straight slopes and only a small curature radius at the divides (plates 1 and 2). On the basis of detailed profile plotting of slopes in the field and plane table mapping it appears that relief in the first area is about 20 times the second, but drainage density is only 1/20 as great, so that the slope angles are of the same general order of magnitude (fig. 2, E, F). If land slopes were perfectly straight from divide to base, the relationship of relief to drainage density would be approximately

$$\tan\theta = \frac{V}{\frac{1}{2D_d}} = 2VD_d$$ where θ = slope angle

V = relief (average vertical distance between divide and channel)

D_d = drainage density

For example, it was found in the Perth Amboy locality that the mean of a large number of measurements of vertical distance between channel and divide was approximately 6.0 feet, or 0.00114 miles. Drainage density sampled from several basins was 500 (that is, 500 miles of channel per square mile of area, projected upon a horizontal plane). Then

$$\tan\theta = \frac{V}{\frac{1}{2D_d}} = \frac{0.00114}{0.00100} = 1.14$$

and $\theta = 48.7^\circ$

Note that the mean of slope readings in this area as shown in figure 2, sample F, was 49.1°. One would not normally expect such good agreement between calculated and observed slope angles, and because the range of error has not been investigated, the coincidence may be misleading.

Relations of Slopes to Channel Gradients.—Davis (1909, p. 266-268) clearly stated the concept that the slopes of a mature landmass are graded, as are the streams. We may restate this principle by saying that slope profiles are in equilibrium with the channel profiles to which the slopes contribute their debris.

For a given area free of systematic structural control, but subject to uniformly controlling factors of climate, vegetation, soil and stage of development, all morphological characteristics tend to approach a time-independent form. Ground and channel gradients, as well as drainage density achieve a form best adapted to maintaining a steady state in the removal of debris. This is simply an extension of Playfair's Law to include all form-aspects of the topography.

If the type of adjustment described above actually exists, one would expect the angle of slope of valley walls to vary systematically with gradient of channel at the slope base. Steep ground slopes would be expected to correspond with steep channel gradients; low ground slopes with low stream channel gradients. This relationship has been stated by R. E. Horton (1945, p. 285) who uses the definition

$$\text{slope ratio} = \frac{S_c}{S_g} \quad \begin{matrix} \text{where } S_c = \text{channel slope} \\ \text{and} \quad S_g = \text{ground slope} \end{matrix}$$

Ground slope can be determined by the field methods previously described in this paper. For each slope reading the channel gradient at the base of the slope would need to be measured. This was not done in the field by the writer, but the general trend of the slope ratio was obtained from large-scale topographic maps, including two which were specially mapped for the present study. Figure 8 shows the means of ground slopes and channel slopes plotted on log-log paper. Each point represents means of a large number of measurements of ground slopes and channel slopes. Because samples were taken from maps and the correlation is believed to have wide inherent spread of values, a curve was fitted by inspection. We might say that, if these data are representative of general conditions, ground slope varies as somewhat less than the first power of channel slope, and that the slope ratio tends to range from 1/5 or 1/4 for low values of slopes, up to about 1/2 in the higher values.

There are several uncertain elements in the foregoing analysis. Data from a greater number of regions would be expected to modify the estimating equation considerably. Substitution of careful field measurements for map measurements would increase the confidence in the data. It is further obvious that channel slope steepens rapidly toward the head of a valley, whereas ground slope tends to remain nearly constant along the

Plate 1. Topography of Verdugo Hills. Cabrini Canyon, south side of Verdugo Hills, Los Angeles Co., Calif. Slope in foreground faces northwest, had chamise-chaparral cover prior to burning. Canyon is about 200 feet deep.

Plate 2. Topography of Perth Amboy badlands. Badlands in clay-sand backfill, Perth Amboy, N. J. Relief in this photograph is 20 to 30 feet. This topography is similar in form-characteristics to that shown in plate 1.

sides of the valley, as the frequency distribution studies show. To minimize this variable, which can easily vitiate the results, readings were made along second-order stream basins, near the point where they are formed by the junction of two first-order streams (Horton, 1945, p. 281). This assures that all data come from the same relative position in the drainage system. Further standardization is desirable.

There is a suggestion from the data of figure 8 that climate has a profound influence on the slope ratio. Areas 7 and 9, which lie to the right of the line of the estimating equation, and area 8 which is on the line, have typical bare ground surfaces of badlands, or are lightly covered by chaparral, as in the Mt. Gleason area (7). Here one might expect a given slope of valley side to supply proportionately more detritus to the channel than a comparable slope in vegetation-clothed regions

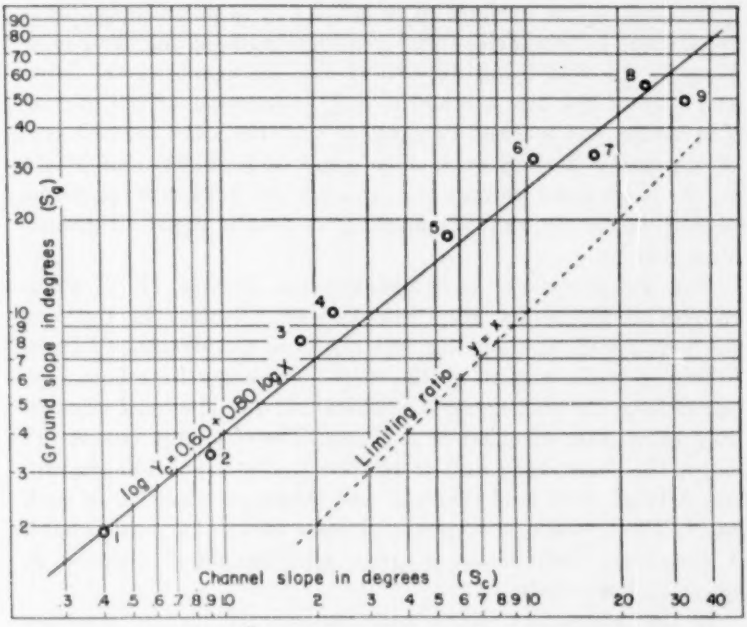

Fig. 8. Slope ratio, $\frac{S_c}{S_g}$, for nine maturely dissected regions. 1. and 2. Grant, La., 3. Rappahannock Academy, Va., 4. Belmont, Va., 5. Allen's Creek, Ind. 6. Hunter-Shandaken, N. Y. 7. Mt. Gleason, Calif. 8. Petrified Forest, Ariz. 9. Perth Amboy (clay fill), N. J. All data from U. S. G. S., A. M. S. or special field maps.

in the humid climates. The thinly vegetated areas would require relatively steeper channel gradients for the transportation of the greater quantity of detritus. In the two cases lying to the right of the line the channel slope is high in proportion to ground slope. While this could easily be merely the result of chance sampling, it is in agreement with the deduced behavior. On the other hand, well-vegetated slopes in the humid climate would tend to supply less detritus because of the increased surface resistivity and infiltration capacity, and would be associated with relatively lower channel slopes. As if to verify this deduction, points 3 through 6, representing humid regions, lie to the left of the line of the estimating equation. As this could readily be the result of chance, the observation merely makes more intriguing the prospect for a more adequate investigation of this phase of equilibrium relationships.

Comparison of Slope Data of Maps with those of Field Observations.—The problem of reliability of slope readings taken from maps in comparison with readings made at the same locations in the field is an important one, inasmuch as the labor and cost of the first method is only a fraction of the second. The writer was inclined to suppose that the most recent maps of the Army Map Service on a scale of 1:25,000 and of the U. S. Geological Survey on a scale of 1:24,000 made by photogrammetric methods would give results equal to ground observations.

For test purposes the Shandaken and Hunter, N. Y. quadrangles of the Army Map Service were selected. In the field the writer walked along the side slopes of five drainage basins, following trails marked on the maps. The maps have been prepared from air photographs. Planimetric detail seemed remarkably good when checked in field use. The drainage basins are large, the slopes long and of relatively simple, smooth character. A total of 60 field readings was taken, or about 12 in each basin. These readings were spaced from 50 to 150 yards apart. A frequency distribution diagram of these data is shown in figure 9, lower half.

In the laboratory slopes were measured from the contours along the same stretches of the trails. Approximately the same number of readings, 58, was taken, and while these are sampled from zones corresponding to those in the field, they are equidistantly spaced and do not coincide exactly with the field

readings. A frequency distribution diagram of these readings is shown in figure 9, upper half. A comparison of statistical measures of the two distributions is given in table 3.

TABLE 3

Summary of field and map data of five drainage basins, Hunter and Shandaken Quadrangles, N. Y.

DRAINAGE BASIN	FIELD DATA $\bar{X}$		MAP DATA $\bar{X}$	
Hunter Brook	27.7°	N = 60	26.9°	N = 58
Becker Hollow	30.0°	$\bar{X}$ = 32.69°	30.7°	$\bar{X}$ = 30.72°
Taylor Hollow	32.8°		28.3°	
Notch Lake Hollow	33.4°	s = 8.24°	31.9°	s = 6.20°
Shanty Hollow	35.5°	$s_{\bar{x}}$ = 1.07°	34.4°	$s_{\bar{x}}$ = 0.81°

Examination of the histograms and summary table shows that the field distribution has a higher degree of irregularity

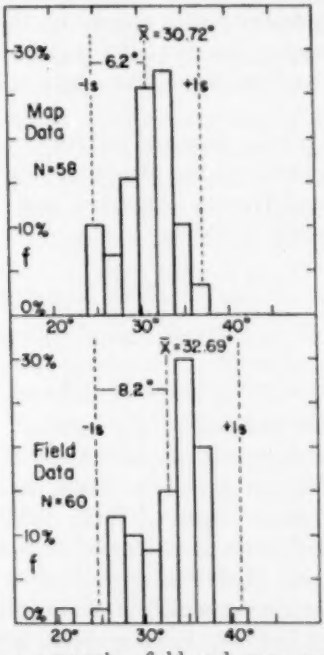

Fig. 9. Histograms comparing field and map samples of slope angles from the same drainage basins. Shandaken and Hunter, N. Y. quadrangles, A. M. S. 1:25,000.

than the map distribution. Dispersion is greater in the field data, with an estimated standard deviation a full 2° greater and with two end classes which are not present in the map data. It appears that use of the map tends to reduce the dispersion and remove irregularities. This might be expected if the drawing of contours in preparation for reproduction results in increasing the degree of parallelism present in the original contours.

The field data are strongly bi-modal because, of the five drainage basins used, two have low but similar means; the other three are relatively high. Note that while the map data also show a bi-modal tendency, it is greatly reduced; the sequence of means is not in quite the same order as in the field data. The greater homogeneity of the map data is again apparent.

Of greatest interest is the difference in means, a whole 2°. We might at first suppose that the processes of mapping and map drafting have caused a reduction in slopes, through the process of drawing the contours evenly spaced on the map, even where steeper and less-steeper portions of the slope are actually present. This would tend to lower the angle read from contours alone.

Are the field and map means significantly different? To test the difference, the ratio of the observed difference to the standard error of the difference (Croxton and Cowden, 1946, p. 319) was computed as follows:

$$\frac{x}{\sigma} = \frac{\bar{X}_1 - \bar{X}_2}{\sigma_{\bar{x}_1 - \bar{x}_2}} = 1.462$$

On the normal curve this value of $\frac{x}{\sigma}$ lies at such a position that the area under the tail of the curve is 0.07. The difference is therefore not significant but the level of significance is not convincing. We can make the following statement: Even if the map is an exact replica of the field topography, we should expect a difference in means of any 2 samples of this size to be two degrees (1.97° exact) or more in 15 out of 100 times because of chance variations in sampling alone. Hence we cannot say that the map is inaccurate. Even if a very significant difference were present, it would not necessarily mean that the map were at fault. Differences resulting from the map

and field methods of reading slopes might cause the observed differences in means.

In conclusion, we may say that while a fairly close agreement exists between field slope data and those taken from the best available topographic maps, the inconsistencies are of too great an order to permit significance studies between small groups of field and map data. It is advisable to use only the one type of data, preferably the field observations where these can be had.

A Tentative Classification of Graded Erosional Slopes.— As a result of frequency distribution analysis and field study of slopes in a wide range of localities, the classification of erosional slopes into three general groups seems feasible:

(1) *High-cohesion slopes.* Slopes underlain by cohesive, fine-textured materials such as clays or clay-rich soil or by strong, massive bedrock, such as granite, schist or gneiss tend to have means in the range 40 to 50° and sometimes higher in regions of strong relief. These slopes are higher than the angle of repose of the loose, dry fragments of the same materials, so that taluses of lower surface angle may accumulate at the slope base where material rolls or slides down the slope and is not swept away by streams. These steep slopes are subject to occasional rapid flowage and sliding movements of the soil or surficial layer following torrential rains. Where the slope has a thick soil of weathered, clay-rich material resting on a resistant, massive crystalline rock, a debris-avalanche may strip off the entire layer, exposing a slope of bare rock (Bryan, 1940, p. 262-263; Freise, 1938).

Examples of high-cohesion slopes are found in badlands, such as the Petrified Forest, New Mexico, or in eroded clay dumps along the Raritan River, New Jersey. In the Verdugo and San Rafael Hills of the California Coast Ranges are examples of slopes of similar steepness where a soil layer with moderate vegetation rests on deeply decomposed diorite or metasediments. Bailey (1948, p. 304) has described stable vegetated 60-degree slopes underlain by fine-textured soils with well-developed profile. He attributed the high angle to binding and protective action of vegetation, principally grass. Examples where bare, hard, massive crystalline rock forms the slope were seen in the Blue Ridge in North Carolina.

Thus steepness of slope, alone, without regard to scale of

slope length or drainage density, can exist under a wide variety of lithologic conditions. There is the common property of maintaining a slope angle above that of the angle of repose of coarse fragmental materials because the slopes possess a high degree of cohesion or strength. All seem to require also that a steep-gradient stream system in process of vigorous corrasion be present.

Bryan has pointed out (1940, p. 263) that for steep slopes of the tropical regions there is nothing to indicate that the slopes should flatten with time. We might reason that, so long as a steady state prevails in which the streams are corrading their channels and constantly removing the detritus from the slope base, conditions of vegetation, climate and lithology remain constant, the slopes would maintain a fairly constant angle in equilibrium with the other factors. However, just as graded streams gradually regrade their profiles to lower gradients with generally decreasing land relief, the contributing slopes might be expected to be gradually reduced in gradient, the system maintaining a steady state through any given short period of time.

(2) *Repose slopes.* Slopes which shed loose, coarse rock particles may be controlled by the angle of repose of those materials provided that vigorous stream corrasion into the slope base promotes the maintenance of the maximum or near maximum repose angle. Meyerhoff (1940, p. 251) seems to have included this type of slope in the term *gravity slope.* Bryan (1922, p. 43) terms certain desert mountain slopes *boulder-controlled slopes.* He states that they are commonly in the range 30-35° and that the grade of the slope is the angle of repose of the average-sized joint fragment.

Repose slopes are illustrated by certain drainage basins in the Catskill Mountains (see figure 9) where a coarse layer of angular sandstone and conglomerate mantles slopes whose mean was found to be 32° in five first-order drainage basins.

The term *talus-slope*, referring to slopes of slide rock accumulation made by accretion of particles rolled or dropped from a higher source, should not be confused with repose slopes here described. The latter are essentially erosional, having only a thin veneer of loose particles over the parent bedrock.

Erosional repose slopes are observable in gravel pits where glacial-fluvial sands and gravels are being excavated. Left

undisturbed, a fresh vertical cut into a gravel bank will recline to a straight slope equivalent to the angle of repose of the loosened particles, but composed of the almost bare, undisturbed, bedded sands and gravels. On this slope, which merges into a true talus at the base, particles will just slide or roll when dislodged from the parent mass. Laboratory analysis of angles of repose in fragmental materials (Van Burkalow, 1945) shows that repose slopes have distribution characteristics similar to the valley slopes described in the present paper.

Slide-rock slopes might be expected to maintain a constant angle as a region is progressively denuded, provided that the streams maintain a vigorous corrasion which saps the valley walls and maintains the maximum angle of the slide-rock fragments.

(3) *Slopes reduced by wash and creep.* Where channel corrasion is greatly reduced and channel gradients are low, due to onset of a late-mature stage, slopes are not maintained at the maximum angle by basal corrasion. Here sheet-erosion, rain beat and creep reduce the slope to angles well below the angle of repose. Bryan (1922, p. 46) terms these slopes *rain-washed slopes* and states that they are developed on fine-grained materials, readily subject to removal by rain-wash. Meyerhoff (1940, p. 251) terms these *wash slopes* and states that they seldom exceed 15°. He regards them as secondary forms which replace the steeper varieties by encroachment at the base. In the W. Penck system these would be classed as *Haldenhänge.*

Examples of slopes reduced by wash and creep were found to have means ranging from 20° to as low as 1½° (see fig. 2, A, B). It is postulated here that the slopes were reduced gradually in angle as the relief of the region diminished and stream gradients declined. Some evidence favoring a gradual decline of slope angle rather than replacement of a steep slope by a distinctly lower slope is discussed in a later section.

Summary Statement.—The application of standard methods of frequency distribution statistics to study of slope angles is of value in two principal respects: (1) It provides a standardized quantitative method of describing the characteristics of maximum slope angles within a small area, although it does not rectify fundamental errors of judgment made in the

sampling process. (2) It provides a tool, through the method of significance of difference of sample means, of evaluating the results of field measurements and thereby prevents the drawing of unwarranted conclusions from numerical data. At the same time it may give confidence in certain conclusions based upon truly significant differences in sample means.

The measurement and analysis of real landforms is an inductive method, contrasting strongly with the purely deductive projective-geometric treatment of slopes used by Lawson (1915) and Putnam (1917) and recently revived by Bakker and Le Heux (1946). The latter method lays great stress on precision attained by setting up initial assumptions and deducing the slope profile to be expected. Whether the initial assumptions or deduced profile development bear any resemblance to real landforms is dubious at best, because only one process, out of several acting together, is selected for analysis.

(*To be continued*)

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THE CHEMICAL KINETICS OF THE KATMAI ERUPTION

C. N. FENNER

PART II

ANALYSES OF PUMICES

Probably the most convincing proof of the processes at work in the magma is provided by the analyses of the pumices.

In preparation for analyses, if the field sample consisted largely of lumps of pumice, many lumps were picked out and ground to fine powder. The lumps in any sample show considerable variation among themselves because of imperfect magmatic mixing, and an endeavor was made to take a representative sample. Actually, the attainment of this objective was not thought to be of the greatest importance. Each lump of pumice was believed to be in effect the result of mixing of two end members—the new magma and the old rocks of the crater—and though the composition of the sample taken for analysis might depart from that of the sample as a whole, it should still have a composition proportional to a mixture of the two, or, in a geometrical construction, it should lie on the lines between the two ends. The most important point was to determine if this was true. Nevertheless an effort was made to have the part taken for analysis represent the stratum of ashfall in which it occurred.

The thinner strata were generally of finer grain. The material of each of these was simply mixed, and a part taken.

Twelve of the thirteen layers of ashfall at Camp IV were analyzed. No. A-184, a 6 mm. layer, was left out as being insignificant. These analyses are given in table 1. Eleven of the twelve analyses, recalculated to 100 per cent after omitting water and minor ingredients and with all iron calculated as Fe_2O_3, are plotted on the diagram figure 3. No. A-187 is not included. It is a 35 mm. reddish-brown and purple sand or mud at the top of the ashfall. Its composition is much out of line with the other layers. What it represents is uncertain—possibly a wind-blown dust.

In an article published several years ago (Fenner, 1926, p. 700) the compositions of a large number of older igneous rocks of the Katmai region, together with A-175 of the 1912 eruption, were plotted on a similar diagram. The indicative

points of these analyses were shown to lie close to straight lines. If now the lines of the older diagram be superposed on figure 2, all the points of figure 2 are found to lie very close to them. The lines of the older diagram would probably be accepted

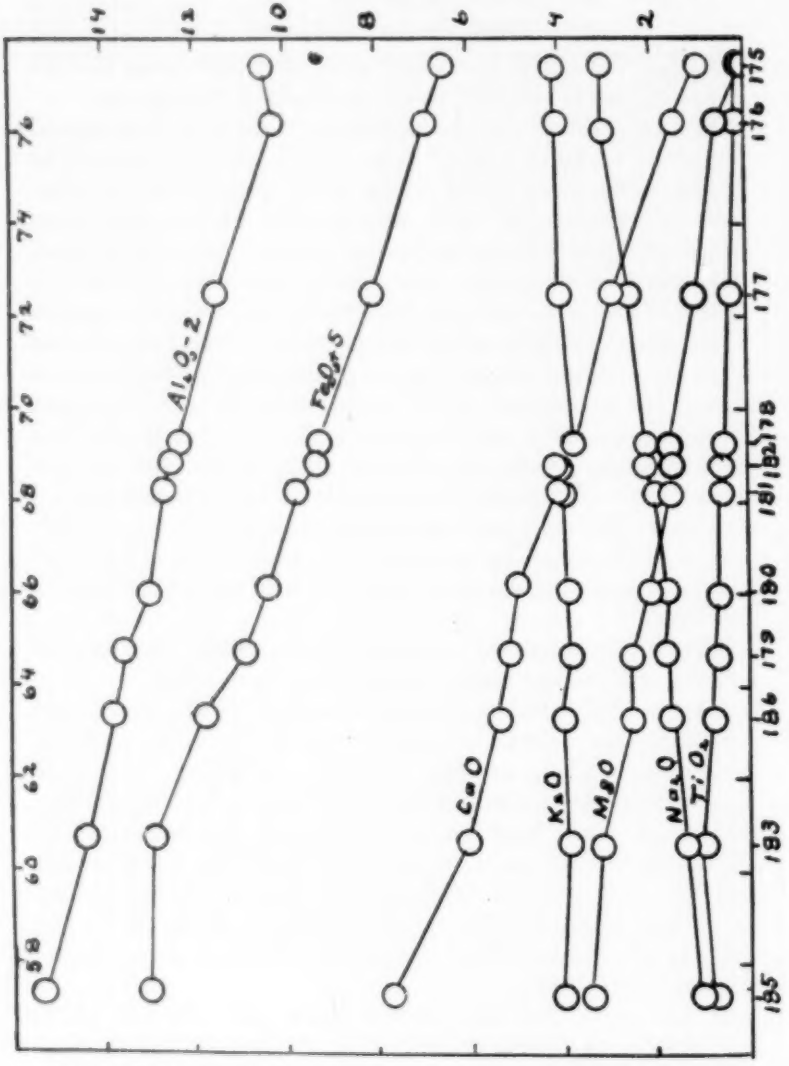


Fig. 2. Diagram of analyses of pumices in successive layers of Katmai ashfall.

without question as representing the average lines of variation of the pumices of the 1912 eruption. This should be expected if the rocks of the crater walls had a composition in accord with the lines of variation of the old lavas of the region and if the pumices represent the assimilation of these wall-lavas by the new magma. Under any other supposition the agreement would be extraordinary. A similar but more exact and convincing demonstration was worked out as follows: The average composition of all the strata of the ashfall was calculated by taking the composition of each stratum, giving it a weight in proportion to its thickness, and combining the whole. The results of this calculation are included in table 1. This average composition was then plotted on the straight-line diagram of older rocks, Alumina was found to be 0.38 per cent low, ferric oxide 0.19 per cent low, and each of the other constituents, magnesia, lime, soda, potash, and titania, showed less than 0.1 per cent discrepancy.

This agreement, I think, is remarkably good. Several factors might have prevented such close agreement. The lavas of the peak that were assimilated might not have had quite the composition that would conform to the straight-line diagram, winnowing by winds during the downfall of the ash might have had a selective effect, incorporation of sediments might have caused departure, and there might have been analytical errors. We thus have the strongest confirmation that the pumices are simple mixtures or assimilation products of the old crater walls and the new magma.

In the composition of the pumices there is little or no indication that the sedimentary rocks through which the volcanic conduit rose made any important contribution to the pumices, yet it might be supposed that these rocks would be attacked and assimilated as readily as the lavas. Why were they not? I believe the answer involves one of the fundamental theses of this article and gives it strong support. It is that the exothermic reactions by which the magma was enabled to assimilate the wall rocks were developed only in the upper portions of the lava column as it lay in the crater—those portions from which gases were able to escape and set in motion the mechanism of exothermic internal reactions.

We may draw another important conclusion from the analyses. We have evidence that sedimentary rock was not assimilated

to any important degree and we know that no great quantity was thrown out mixed mechanically with the pumices. What, then, became of the sedimentary rock that occupied a great part at least, of the space where there is now the huge crater pit? We may answer with considerable assurance that it collapsed into the depths after the eruption was over.

In early papers I had touched upon this problem, but the evidence then at hand did not seem sufficient to answer the question definitely. I was inclined to the view that sedimentary as well as igneous rock was involved in the large amount of contamination that the pumices show. Dr. Howel Williams, in correspondence, favored cauldron subsidence at Katmai because of the many instances of this action that he had found in great calderas in various parts of the world (1941). Mount Katmai can now quite certainly be added to his list.

Additional evidence is provided by consideration of the Katmai incandescent tuff-flow. This tuff lies on top of the Katmai ashfall (plate 1), and therefore was the final act of ejection. If the present vast caldera had existed at this time the material of the tuff-flow would have had to fill it before it spilled over the rim, and this is hard to imagine. Furthermore, the depression (glacial trough) on the present southeast rim that would have been the outlet channel for the tuff if present conditions existed at that time, is matched by a similar depression on the northwestern rim, at no higher elevation, that would have offered equal opportunity for overflow. This northwestern sag would have led part of the overflow down the western side of the mountain into the Valley of Ten Thousand Smokes, along the course that we took in our 1923 ascent of the mountain. We saw no evidence of the tuff on our ascent on this side, whereas on the southeastern side it is plainly evident. The inference is that until the end of the eruption, including the final outburst of the Katmai incandescent tuff, the present caldera had not been formed, but that some remnant of the peak in which the crater lay was still in existence, and that its configuration was such as to direct the flow of incandescent tuff to the southeastern side. This condition may also have been a factor in causing heavier ashfall on the southeastern side.

Calculations have been made from the analytical data now on hand to determine in what proportions the older lavas were assimilated by the new magma. Since the composition of the

pumices fits (very closely) the older diagram of straight lines between the two end members, we have a simple geometric relationship such that any one of the constituent oxides is proportionately representative of any other, and we might use any one of them in calculations. Silica percentages will thus be used as most convenient and least likely to exaggerate minor discrepancies.

In the calculated composition of *pumices as a whole* (table 1) a silica content of 69.13 per cent was found. The new magma, A-175, had 77.43 per cent silica (on a volatile-free basis), and the mafic rocks that it assimilated have been assumed (from the character of their phenocrysts) to have had 54 per cent silica.

Let x = amount of mafic rocks assimilated.

Then $54x + 77.43\ (1-x) = 69.13$.

$\therefore x = 35.4$ per cent of assimilated mafic rocks and 64.6 per cent of new magma, A-175, in the *average pumice*.

Part of the assimilated rock was incorporated directly in the melt and part was left undissolved as phenocrysts (xenocrysts) of the contaminated product.

Although the new magma, as it first appears in the lowest stratum (A-175) of the ashfall, shows no contamination itself, its exothermic reactions doubtless helped as a source of heat, supplied both to the rocks engulfed in it and to wall rocks against which it lay and which subsequently became engulfed. Likewise, gases given off, with their mutual reactions not yet completed and still reacting vigorously with each other exothermically, added to the effective heat supply.

It is of interest to learn how much of the incorporated mafic rock was actually dissolved by the new magma and how much was left undissolved. It is clear from the petrographic studies that the groundmass of the old lavas and also the aphanitic lavas as a whole were quickly dissolved, but that the phenocrysts were less rapidly attacked. Calculations were made on the pumice of *layer 180*. This layer is the thickest of the series and one of the most homogeneous. It is somewhat more mafic than the pumices as a whole, but the results, suitably modified, are applicable to all.

As a first step, using the same form of equation for A-180 as was applied just above for the average pumice, but using the silica content of A-180 (66.12 per cent on a volatile-free basis),

calculation gives 48.12 per cent of old rocks incorporated, that is, partly dissolved and partly left as undissolved phenocrysts (compared with 35.4 per cent in pumices as a whole).

In the next operation the amount of mafic rock actually dissolved in the glass of A-180 is to be determined. This glass has an index of about 1.489, though striae of slightly higher index attest inhomogeneity. In ordinary calc-alkalic rocks an index of 1.489 in a glass indicates a composition of about 72 per cent silica.

Then

$54x+77.43\ (1-x)=72$

$x = 23.1$ per cent of mafic rock dissolved in the *glass of A-180*. Later, by another calculation with different data, this will be confirmed.

In order to obtain further information and to check data previously obtained a specific gravity separation and partial analysis of the products were applied to pumice A-180.

A portion was crushed to pass 100-mesh and a separation was made in a mixture of methylene iodide and benzol. It was hoped that a fairly clean separation into heavy and light fractions could be made in this way, but such separations are difficult when the specific gravities approach each other closely or overlap. The light fraction obtained was found to have a considerable amount of heavy minerals, mostly feldspar, estimated at 10 per cent, and the heavier fraction contained an estimated 5 per cent of glass. Although the separation was not clean, approximations were obtained which are believed to be fairly close to correct results. Certain circumstances or coincidences are favorable for approximate calculations. In a basalt or basaltic andesite of 50 to 55 per cent silica the feldspars alone, the remainder of the rock without the feldspars, the groundmass alone, and the remainder of the rock without the groundmass, all are likely to have a silica content not differing greatly from 50 to 55 per cent.

A determination of alkalies in the heavy fraction of the gravity separation gave 3.61 per cent Na_2O and 0.614 per cent K_2O. (See table 4.) Since there is a little glass in this heavy fraction, and this glass carries alkalies contributed by A-175, the figures should be modified in order to obtain the amounts apropriate to the heavy minerals alone. This correction is very small, but the final figures become 3.26 per cent Na_2O and

0.55 per cent K_2O in the heavy minerals. When these figures are plotted on the straight-line variation diagram, they fit at 53 to 54 per cent silica. They become increasingly inconsistent as we move away from these figures.

TABLE 4

Partial analyses of heavy and light fractions of specific gravity separation of pumice A-180.

	Light Fraction	*Heavy Fraction*
SiO_2	69.78	....
Na_2O	4.07	3.61
K_2O	2.11	0.64

This result is confirmed by another calculation in which wholly different data are used, as follows: The trend of potash content of the pumices shows a regular decrease of silica. When, by a test calculation, silica is taken as 50 per cent, potash has become a minus quantity. This is clearly impossible; therefore the silica content of the assimilated rocks must have been more than 50 per cent. The corresponding upper limit is found from the composition of the pumice A-185. This pumice contains 57.59 per cent silica (volatile-free basis) and is the most basic of the ashfall strata, but the pumices in it are evidently of variable composition. Some lumps are gray, with many dark xenocrysts, and others are almost pure white and are nearly free of xenocrysts. Partial analysis of these latter give the values of 185X of table 1, corresponding nearly to the purest pumice A-175. This is of much interest in itself, as demonstrating the continuous welling-up of fresh magma. Its application here is that it shows that A-185 would be more basic if its content of A-175 could be removed. Therefore, the undiluted basic rock carried less than 57.59 per cent silica. Thus we have bracketed the silica content of assimilated basic rock between 50 per cent and 57.59 per cent, and the original assumption of 54 per cent is closely confirmed.

The *light* fraction of the specific gravity separation of A-180 was a mechanical mixture of 10 per cent (estimated) heavy minerals (mostly basic feldspar) of 54 per cent silica content with 90 per cent glass. The glass is a solution of mafic rock in the new magma A-175. A special analysis (table 4) showed this light fraction to contain 69.78 per cent silica.

Let x=silica percentage of the glass alone.

Then $5.4+0.9x=69.78$.

x=71.5 per cent silica in glass of A-180. From the refractive index of this glass a silica content of 71 to 73 per cent was estimated in a previous calculation, and on a basis of 72 per cent silica it was calculated that 23.1 per cent of mafic rock was dissolved in the glass of A-180.

With the data now on hand it is further calculated that about 53 per cent of the pumice of A-180 is glass.

Finally, in our study of A-180, we have the partial analysis of the lighter fraction of the specific gravity separation listed in table 4, showing 69.78 per cent silica, 40.7 per cent soda, and 2.11 per cent potash. This fraction consists mostly of glass but partly of feldspar crystals. Since both the feldspar crystals and the mafic rock as a whole have approximately 54 per cent silica, this light fraction is a mixture (partly in crystals and partly in glass) of the magma A-175 with various substances of 54 per cent silica content. When the analytical results are applied to the straight-line variation diagram, the soda and potash of the analysis should fall at the points where the ordinate erected at 69.78 per cent silica intersects the lines for soda and potash of the diagram. When so tested the correspondence is found to be 4.07 per cent compared with 3.90 for soda and 2.11 compared with 2.23 for potash.

In several ways we have found in the analyses confirmation of the belief that the pumices are products of the assimilation of great quantities of the old mafic rocks of the volcanic crater by the new rhyolite magma A-175. Following is a brief recapitulation of the chemical evidence and its significance.

1. The lines of variations of composition of the pumices, as shown in figure 2, correspond very closely with the corresponding diagram of older igneous rocks of the Katmai region.

2. The composition of all the pumice strata taken together likewise falls almost exactly on the older diagram.

3. From these correspondences it is concluded that sedimentary rocks did not enter to a perceptible amount in the hybridization—only the basic lavas of the mountain top in which the crater lay.

4. It follows further that the evolution of heat for assimilation was essentially a near-surface effect and was not developed to a great depth of the new lava (that is, it did not penetrate down to the horizon where the lava was in contact with sediments).

5. This last is in accord with the further fact that explosivity affected only the upper portions of the lava column at each outburst.

6. The formation of the present great caldera was caused by cauldron subsidence—solution of sediments was little if at all contributory.

7. Indices of refraction of feldspars indicate that the old lavas contain 54 per cent silica.

8. From silica content (by analysis) of average pumice and silica contents of new magma and old rocks respectively, the average pumice is found to be made up of 35.4 per cent of assimilated mafic rocks (partly dissolved in glass and partly left as undissolved xenocrysts) and 64.6 per cent of new magma A-175.

Special computations were made on the pumice of layer A-180 of ashfall.

9. On similar data as for the average of all pumices A-180 consists of 48.3 per cent of old rocks (dissolved and as xenocrysts) and 51.7 per cent of new magma A-175.

10. From index of glass of A-180 as evidence of a silica content of 72 per cent it is found that the glass of A-180 contained 23.1 per cent of mafic rock dissolved in it.

By making a specific gravity separation in A-180 and partial analyses of the fractions, further data were obtained.

11. Determination of soda and potash in the heavy fraction of A-180 gave results that fit the variation diagram at 53 to 54 per cent silica, thus confirming the previous conclusion No. 7 from different data.

12. From the silica content of the light fraction of A-180 we find that the glass contains 22.2 per cent of mafic rock, compared with 23.1 per cent as found under No. 10 by another method.

13. It is found that about 53 per cent of A-180 is glass.

14. The general diagram (fig. 2) shows fluctuations of relative amounts of old rock and new magma in the pumices. There is increasing quantity of old rock from A-175 to A-179, decreasing quantity to A-182, increase to A-185, and decrease to A-186. These fluctuations are attributed to conflicts between amounts of old rocks assimilated and fresh supplies of A-175 welling up into the crater. This is confirmed by the heterogenous character of the pumices and the presence of white pumice in

each layer; further by the fact that white pumice picked out of the most basic sample (A-185) and analyzed (185X) has nearly the composition of the pure rhyolite.

15. Partial analysis of the light fraction of the specific gravity separation of A-180 (table 4) shows amounts of silica, soda, and potash fitting the straight-line diagram of older rocks.

I submit that this evidence is an extraordinarily concordant confirmation of the thesis of this article. To be added to it is the field evidence that has been cited of the characteristic of the pumices in the ashfall and the petrographic evidence by which the actual process of solution of xenoliths is made visible and the xenocrysts of the pumices are traced directly back to the phenocrysts of the old lavas. There seems to be no escape from the conclusion that the pumices are the result of the assimilation of great quantities of the old rocks of the crater in the new magma. If this evidence is not sufficient, there is more to be cited in the phenomena of Novarupta and of the incandescent tuff-flow in the Valley of Ten Thousand Smokes.

A short description of the results of two other analyses of Katmai products remains to be given.

Sections of the ashfall at two sites in Katmai Valley have been described. Three others studied were of essentially the same character, except that the thickness of strata decreased in going southward. Among the samples of these taken, one A-505, corresponded in position in the section and in makeup to A-181. An analysis was made as a check and is given in table 1. The composition is almost a duplicate of A-181, although this stratum was of heterogeneous composition like all the strata of the ashfall. It was mostly a light-gray pumice, but varied from a white pumice with an index of 1.487 and rare phenocrysts of sodic feldspar to a dark pumice of index 1.505 and many phenocrysts of pyroxene, feldspar (labradorite), and iron ore.

The horseshoe island on the floor of Katmai crater was evidently formed by a small extrusion of lava after the cauldron subsidence took place. The analysis of this lava is given in table 1 as A-547. This does not fit the general diagram as well as the analyses of pumices do. The type is not very different, but it departs from the composition that a straight mixture of the new magma and the old rocks of the crater give, and in that

way it does not conform with others. This hardly seems surprising. If it is a hybrid rock, the conditions of hybridization were different from what they had been previously. After the collapse of the crater any lava that found exit at the surface had to work its way through a mixed mass of broken and crushed igneous rocks and sediments. Petrographic study of a thin section does not give much further information. A glassy matrix of index 1.490 incloses numerous phenocrysts of feldspar, pyroxene, and iron ore. The feldspars are somewhat variable, but most have a composition of about An_{44}.

THE INCANDESCENT TUFF-FLOW OF THE VALLEY OF TEN THOUSAND SMOKES

In the Valley of Ten Thousand Smokes occurred the great flow of incandescent tuff and the violent explosive activity of the parasitic volcano Novarupta. The processes of assimilation and hybridization here are of the same nature as those described in connection with the ejecta of Mount Katmai, but the evidence is, in some ways, even more clear. In some of the phases of activity assimilative action was less intense and halted at a point where digestion was only half completed. If assimilation had gone only a little further in the main crater of Katmai, the more striking evidences of inhomogeneity would have been pretty well wiped out, but among the products of Novarupta and the Valley[2] vents the inhomogeneities are so evident that they cannot be missed.

The incandescent flow or flows of the Valley apparently constituted the first major outburst of the eruption, for they are covered by a layer of ash from Mount Katmai. In the lower (southwestern) part of the Valley this latter deposit is rather thin; in the vicinity of Novarupta it is presumably thicker because of nearness to Mount Katmai, but it is so mingled with the much greater quantity from Novarupta itself that it cannot be distinguised. Near Novarupta the strata of ash are incomparably thicker than anything found close to Mount Katmai, but they decrease rapidly as one moves away from the vent.

The breaking-out of Novarupta and the innumerable lesser vents in the Valley, in an area where no volcanic activity had formerly been present, seems to have been caused by the following succession of events: When the new magma first rose in the

[2] "Valley," written with a capital V, will be used as a shortened designation of the Valley of Ten Thousand Smokes.

Katmai conduit and before it reached an explosive stage in the crater a portion of it escaped as a sill injected under the floor of the Valley between the nearly horizontal sedimentary rocks that underlie the area. This resulted in fracturing and dislocation in various places (Fenner, 1925). The floor of the Valley was upheaved, the defile of Katmai Pass was broken open, the lower slopes of Mount Trident that face the Valley were badly shattered, a great slice of Falling Mt. collapsed, and Broken Mt. was cut to pieces. From the vents thus produced the great incandescent tuff-flows were poured out. Novarupta was the chief of these vents, and its orifice later became enlarged and it passed into violent eruption. Finally a mass of viscous lava rose from its crater as a dome, about 800 feet (244 meters) in diameter and 200 feet (61 meters) high, surrounded by a high wall or "corona" of ejected pumice and glass-blocks. (For illustrations see Griggs, 1922, pp. 238, 276, 280, 300; Fenner, 1920, p. 588; 1923, pp. 15, 44, 53, 58, 60, 63; 1925, p. 203.)

Vents broke out in both branches of the V-shaped Valley for a distance of 12 to 13 miles (19 to 21 km.), from Mount Trident to Three Forks, and in a branch extending southerly up over Katmai Pass (fig. 1). Probably all were orifices of extrusion of incandescent tuff-flow, and they were sites of intense fumarolic activity for years afterward, but in 1923 most of them had vanished or the activity had become very weak. The magma that rose in them behaved in a similarly remarkable fashion to that in Katmai crater. Instead of exploding at once, it lay for a time quiescent in the vents while it attacked and assimilated the rock with which it was in contact. During this interval magma continued to well up slowly from below and mingle with the contaminated magma. Thus were produced the contrasting layers that are so striking in the myriads of specimens of pumice. A typical specimen of these is illustrated in plate 2. Determinations of silica in this specimen by E. T. Allen gave 74.70 per cent in a white band and 60.40 per cent in a dark band.

There is a great difference in the character of the incandescent tuff between the upper and lower parts of the Valley. In the upper Valley the pumices are in general aspect gray, or even dark brown, and contain large quantities of mafic phenocrysts. In the lower Valley the pumice corresponds to the first ejecta A-175 from the Katmai crater; that is, it is pure white or very

pale buff and contains only a few small phenocrysts of quartz and oligoclase-albite feldspar. E. G. Zies has given a table of compositions of four samples of the pure rhyolite from different sites of the Katmai eruption (1929, p. 56). One is an analysis by Steiger of a pumice collected by G. C. Martin, a second by Zies of a Valley pumice collected by Fenner, a third by Zies of the purest Novarupta rhyolite glass collected by Fenner, and a fourth by Fenner of the first layer of Katmai ashfall, A-175. They are almost identical in every respect. A fifth (unpublished) analysis by E. T. Allen of pumice from the stratum A-175 corresponds.

In the lower Valley occasional specimens of the light pumice show streaks of sharply contrasting dark brown or nearly black color, but the light pumice is much preponderant in this area. Apparently there was very little attack by the magma on foreign materials here, and it is natural to conclude that its underground travel of many miles from the Katmai conduit, in contact with cold walls, exhausted most of its heat reserve.

It is not possible to say whether extrusions from the many Valley vents were approximately simultaneous or not. More exposures by deep stream trenching would be necessary to show in detail how the dark pumices of the upper Valley give place to the lighter pumices of the lower Valley. There is evidence, however, that explosive activity did not cease immediately with the emplacement of the tuff. In many places blocks of consolidated tuff, individually weighing many tons, were ejected from vents, together with a large amount of fragments. This consolidation of the tuff had been effected by the deposition of minute crystals of tridymite and orthoclase by gases evolved from the tuff after emplacement. Induration and late explosive ejection were most prominent in the upper Valley.

The basement rocks of the Valley are sedimentary strata of the Upper Jurassic. Fragments of sediments are fairly plentiful in the tuff, but basic lavas are much preponderant, and this requires explanation. In the upper part of the Valley the slopes of the adjacent mountains are predominantly lavas. Here are Mount Mageik, Mount Cerberus, Falling Mt., Mount Trident, Mount Katmai, and Knife Peak. Large glaciers descend the slopes of Mageik, Trident, and Katmai to the Valley floor, bringing down volcanic debris. Knife Peak now has glaciers only near the summit, but its lower valleys are filled

with morainal material. The final dumping-ground or outwash of all these glaciers was on the Valley floor, so that the vents from which the tuffs issued broke out in the midst of loose morainal material, prevailingly of igneous derivation.

J. E. Spurr had traveled through this Valley in 1898 and has described conditions at that time (1898-99, pp. 146 and 147). He speaks of the many glaciers coming down from the volcanoes, and their splendid moraines. A stream on the northwest side of Katmai Pass had cut down at least 100 feet through lava boulders. All along the valley leading to the Pass were stratified gravels "which near the trail across the Pass begin to be filled with great angular boulders. This deposit runs quite up to the foot of the existing glaciers."

This describes the condition in most places in the upper Valley when the new lava broke through. It came into contact with thick superficial detritus of basic lavas, but in some areas the detritus was a mixture of lavas and sediments and assimilation effects varied accordingly.

Descriptions will be given of the character of the incandescent tuff in several areas where the nature of the detrital material that was available for assimilation is reflected in the assimilated product. These will include Knife Creek Valley, Katmai Pass, and the area adjacent to Buttress Mt.

Tuffs in Knife Creek Valley: Knife Creek Valley is the southeastern branch of the Y-shaped upper Valley. Many explosion craters occur here. They reach a maximum diameter of 200 feet or more, and a depth of 50 to 75 feet. The rims of many intersect. Their distribution seems to be at random, except for a tendency to follow the course of the Valley near the northeast side, for two or three miles (1.6 to 2.4 km.). In 1919 Allen and Zies found very high temperatures in some of them (1923, table on p. 104), but in 1923 there was either no emanation or only a little vapor at 98° C. In their walls the lowest material exposed is 10 to 15 feet in incandescent tuff-flow (base concealed; total thickness probably great). This is followed by regularly stratified loose ashfall from Novarupta and Katmai, 25 to 30 feet thick. Surrounding the rims is a thick, irregularly stratified deposit of ejecta blown out of the crater itself (See illustration in Fenner, 1925, p. 197).

The tuff was evidently thoroughly indurated when the explosions occurred and was blown out in large and small blocks.

Its composition reflects the assimilation of moraine of variable composition from the nearby mountains. On the southwest are the sedimentary strata of Baked Mt. and Broken Mt. At the head of this branch of the Valley are the westward-facing slopes of Mount Katmai, sedimentary below, igneous above. Several glaciers descend these slopes. On the northeast side is the great mass of Knife Peak, whose slopes seem to consist altogether of lavas. Several large outwash fans spread from gulches in Knife Peak and in Broken Mt., probably 400 to 500 feet (120 to 150 meters) high in one or two cases. Thus a heterogeneous mixture of debris from sediments and lavas formed the valley fill and was readily available for incorporation in the new magma. Notes taken at various sites showed the following characteristics. At one crater the topmost strata contained great quantities of indurated tuff-flow. "The color of this varies from pinkish-brown to dark-gray. The lumps of pumice in these blocks are light-gray to black."

"Banded pumices are common." At another, incandescent tuff "appears at bottom, under the strata of ashfall and strata of ejecta. It is pinkish-brown and 15 feet+ thick as a maximum. Bottom is not exposed. It is unstratified, and contains gray and black pumice, black glass, red shale (many pieces) and andesites (more or less scoriaceous)." At a third crater, the incandescent tuff is not exposed, but the ejecta contains blocks of it, "dark in color, with much black pumice." At a fourth, 10 feet+ of incandescent tuff is visible, very firmly welded. "Color is brownish-red to chocolate."

The variable but generally medium tones of the incandescent tuff at these sites is to be contrasted with the nearly black color at the next sections to be described, in Katmai Pass. This difference is believed to be attributable to the difference in the character of the detritus available at the two sites.

Tuffs in Katmai Pass: Tuff deposits were studied just within Katmai Pass, a little south of a line between Mount Cerberus and Falling Mt. This site is adjacent to a great flow of dark reddish-brown andesite from Mount Mageik, rising several hundred feet in steep cliffs. Nearby are the lava-covered slopes of Mount Trident. The quoted description from Spurr may be recalled, that in this part of Katmai Pass a stream had cut down 100 feet through lava boulders. This was the environment in which orifices of incandescent tuff-flow broke open.

In reading the accompanying descriptions of very mafic tuff it is important not to lose sight of the fact that the only truly magmatic liquid responsible for the multifarious variations among the tuffs is the rhyolite, A-175, and that it was by assimilation of foreign rock, generally mafic lavas, but, in places, sedimentary rock also, that the varieties of tuff were produced. Even among the most basic-looking tuffs the rhyolite is almost certain to make itself evident by appearing in some amount, large or small, of pure white pumice. When we come to a description of the Novarupta dome we shall see the processes of assimilation in arrested stages.

In the section in Katmai Pass whose description follows, the incandescent tuff is overlain by stratified ejecta from Novarupta. The characteristics of the incandescent tuff are due to its outbreak in the midst of a great thickness of lava boulders; the characteristics of the overlying ashfall are due to the environment at the Novarupta vent a couple of miles away.

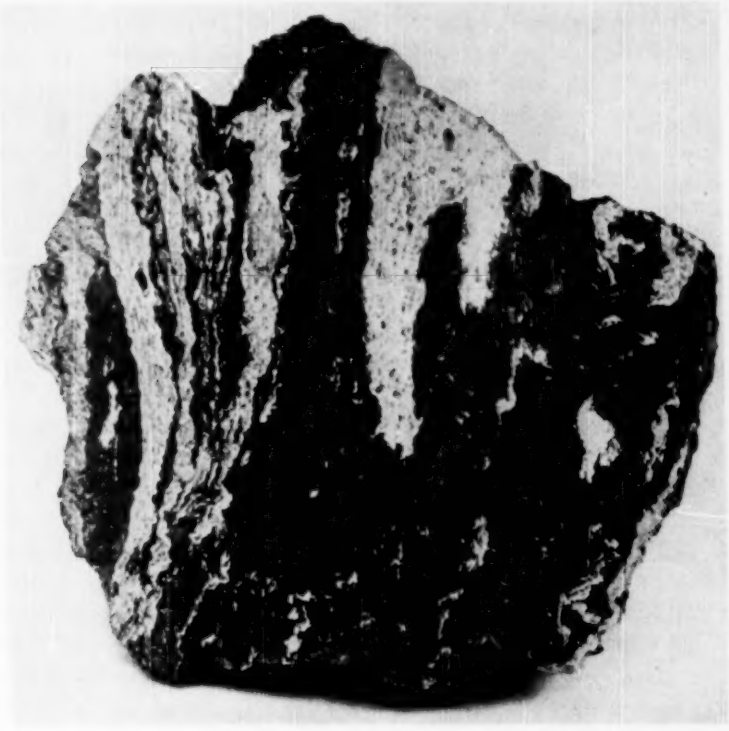
The section follows:

A. Lowest stratum. A thickness of 12 to 13 ft. is exposed; bottom not visible. The general appearance is very dark, due both to many lumps of black pumice and to the dark gray color of matrix of fines. It is practically unstratified, though a suggestion of stratification may be seen along the sides of stream erosion channels. Pumice lumps of 4 to 6 in. (10 to 15 cm.) are common. Much of it is black or very dark brown, with phenocrysts of pyroxene and feldspar in a spongy glass, but light-gray pumice (with some phenocrysts) is also common, and there are many variegated or banded specimens. Fragments of black obsidian (chilled crusts) are present, but no lapilli of sedimentary rock or andesite were observed.

The mass is compact and thoroughly indurated, so that stream erosion has planed off the lumps of pumice and the matrix equally, producing a smooth surface. At the top, for about a foot, this stratum shows yellow and crimson colors, doubtless caused by gas emanations.

Layer A of incandescent tuff is followed by strata of ashfall from Novarupta and probably, to a much less amount, from Katmai. At this stage Novarupta had contributed to the incandescent tuff-flow in the main Valley, and now passed into more violent eruption. Its ejecta were thrown to a distance. The character of the strata of ashfall which follow in this section

Plate 2. Typical banded pumice, Valley of Ten Thousand Smokes.



in Katmai Pass shows that in the crater of Novarupta also rapid assimilation of foreign material was continuing and that eruptive ejections alternated with quiescent periods, during which the chemical reactions within the magma developed.

B. 6 in. (15 cm.) yellow and crimson layer of Novarupta ashfall. Coarse at bottom, with an ordinary maximum of 4 in. (10 cm.). The whole is loose, with not enough fines to fill interstices, but at top the proportion of fines is considerably greater. This layer is not separable from C except by color, and this is a stain, though very prominent and impregnating the pumice thoroughly. Fundamentally the pumice is of the light-gray variety and contains xenocrysts of pyroxene and feldspar. A small amount of lapilli is present—shale and perhaps andesite. Banded pumice was not observed, nor very dark pumice, nor dense glass.

C. 26 in. (66 cm.) light-gray, stained light yellow along certain persistent bands. The make-up is very like that of B, but lacks the deep stain, and proportion of fines is greater. The whole is very loose-textured. It has a pronounced stratification, because of varying proportions of coarse and fine. In B and C and in succeeding layers of the ashfall the lumps of pumice are angular and jagged.

D. 65 in. (165 cm.) thickness variable. The nature and origin of this layer are puzzling. It looks as much like incandescent tuff-flow as like ashfall. In places it contains many very large lumps of pumice up to 2 ft. (60 cm.) in diameter, locally heaped together. Elsewhere lumps of 6 in. (15 cm.) are sparingly distributed. The lumps are very dark brown, light-gray, and variegated. Whether this layer is a second incandescent tuff-flow or Novarupta ashfall, it indicates a great amount of magmatic assimilation but imperfect mixing.

The matrix of fines is dark, and fills interstices pretty fully except in the heaps of bouldery pumice. The top 10-12 in. of the layer is stained crimson. Many small fragments of dark glass are present. Sedimentary rock and andesite are scarce.

E. 6 in. (15 cm.) of ashfall. Is essentially light-gray pumice with phenocrysts, but is stained crimson. Coarse pumice at bottom, more fines at top. This layer is not separable from next except by color. It contains a small amount of obsidian and lapilli.

F. 14 in. (35 cm.) light-gray. Essentially a continuation

of E. Has bands of faint yellow, lavender, and red. It becomes a sand in upper part, and is succeeded by coarser material.

G. 12 in. (30 cm.) light-gray. Like F, but contains much coarse pumice 1 to 2 in. in diameter.

H. 1 8in. (46 cm.) light-yellow. Much coarse pumice 3 to 4 in. (8 to 10 cm.) in diameter. Most of pumice is light-gray, with phenocrysts, but much is light- and dark-banded. Fragments of obsidian and lapilli present.

I. 12 in. (30 cm.) light-gray. Like H but yellow color absent.

J. 24 in. (61 cm.) brownish-yellow. The color (stain) is distinct.

K. 6 in. (15 cm.) of mud. Yellow or brown to lavender.

In this section of Novarupta ashfall the layers do not differ greatly from each other in composition. Although individual pumices show inhomogeneity by their streakiness, assimilation has been so thorough that few xenoliths have survived. The definite stratification indicates waxing and waning of explosive violence.

Another section in Katmai Pass, about three miles south of last, showed at bottom an 84-in. unstratified, compact layer of incandescent tuff-flow exposed in a recent stream cut. It rests upon a mass of loose boulders of reddish-brown andesite, 3 in. to 2 ft. (76 mm. to 61 cm.) in diameter, exposed for a depth of 10-12 ft. It doubtless sifted down among them. Pumice fragments of egg size or more are mixed with fines. It contains great quantities of black pumice, some dark gray and variegated pumice, and some pumice that is very nearly white.

The striking feature is the great amount of black pumice, and its mingling with lighter pumice. The general tone is very dark. On top of this layer of incandescent tuff is about 80 inches of stratified ashfall.

Plate 3 illustrates the character of the incandescent tuff in such deposits as the last two described. The site is a little to the south of Mount Cerberus. The tuff here is highly indurated, and consists of unstratified purplish-brown pumice, with many lumps of gray, black, and variegated pumice scattered through it.

Incandescent tuff near Buttress Mt.:

The southern arm of the Valley is bounded on the eastern, southern, and western sides by zones of faulting. They are be-

lieved to indicate that the Valley floor was uplifted by the injection of the sill of rhyolite in the underlying strata, and that it collapsed when part of the magma escaped as the incandescent tuff-flow. The fault zone is prominent along the eastern side of Buttress Mt. At a point about three-fourths of a mile (1.2 km.) north of the head of this part of the Valley the broken zone exposes 35 feet (10.7 meters) of incandescent tuff in vertical walls. High cliffs of shale of Buttress Mt. are only one or two hundred feet distant, and the outbreak of the tuff here was probably in a talus slope of shale, but outwash from the Mageik glacier may have brought in some lava. The general color of the tuff is reddish-pink, very different from the nearly black tuffs in Katmai Pass. Lumps of pumice in the fine matrix are white, gray, black, or variegated. The black pumice contains phenocrysts of feldspar and pyroxene in a frothy glass, but neither shale nor igneous lapilli were discernible. The mass is well indurated. As the fault zone is followed northward for three or four miles (that is, away from the lavas of Mount Mageik) the proportion of black pumice seems to decrease.

In the several described sections of the incandescent tuff in the upper parts of the Valley, its character seemed to have a definite relation to the detritus deposits where the outbreaks occurred. Where there was nothing but basic andesite boulders, as in Katmai Pass, the tuff is nearly black, though the upwelling of magma gave occasional white pumices. Where the detritus is largely sedimentary, as in parts of Knife Creek Valley and near Buttress Mt., the tuff is prevailingly light-colored.

In the dark brown or black pumices of the upper Valley the index of the glass generally ranges from 1.520 to 1.530, indicating a mafic composition. Exceptionally it may go as high as 1.540. Associated feldspars range from andesine to calcic labradorite. Pyroxenes and iron ore are present. In the associated light pumices the glass has ordinarily an index of about 1.490. Feldspars in these have a composition of about An_{30}, but stray ones may be as calcic as An_{55}.

NOVARUPTA AND VICINITY

The activity of Novarupta went through three well-defined (though merging) phases (Griggs, 1922, pp. 238, 276, 280, 300; Fenner, 1920, p. 588; 1923, pp. 15, 44, 53, 58, 60, 63; 1925, p. 203). In the first phase it contributed to the incandescent tuff-flow. Then it became explosively active, and

threw great quantities of pumiceous ejecta to distances of several miles. Finally, a mass of viscous magma, nearly free of gases, was pushed up from the vent.

Novarupta is close to the foot of one or more glaciers descending the slopes of Mount Trident. These glaciers are now covered with such a great thickness of ash that the area covered by them and even their number is uncertain. They doubtless deposited much lava moraine here, but Novarupta is also very close to the sediments of Broken Mt. In fact, in its explosions it blew away part of the adjacent cliffs. Thus, both lavas and sedimentary rock became involved in the Novarupta magma.

The heavy ashfall from Novarupta has nearly concealed the incandescent tuff-flow that came from its vent. It is identifiable only in a gully on the eastern side, where about 8 feet of it is exposed. (The bad-land topography of this area is shown in Griggs, 1922, p. 298.) Its color is very dark in the mass, but light-gray and variegated pumices occur in it. It is made up mostly of boulders of pumice a foot or more in diameter, together with large blocks of dark glass. These last contain inclusions of pumice, which presumably had been ejected from the lava pool at an early stage, had fallen back, had been caught in a congealing crust, and finally had been spewed out in the mass of the incandescent tuff-flow.

Above the incandescent tuff is a 6-foot transitional layer of pumice boulders, light-gray, black, and variegated, followed by about 30 feet of ashfall in small lumps, stained crimson along certain bands.

The heaviest deposits of ashfall from Novarupta are in the southeastern to northeastern sector, and they are studied to best advantage on the top of Broken Mt., where fault scarps expose vertical sections of 75 feet or more. (Griggs, 1922, p. 244.)

A large area around Novarupta is shattered by faults. Probably the first dislocations were caused by the injection of the sill, as previously mentioned, but the final adjustments of the shattered ground followed the ashfall and involved these deposits. On the southeastern side of Broken Mt. there is a succession of great faults, with downthrow to the southeast, and with total displacement estimated to be 300 feet. From here a zone of faulting in steps and wedges extends toward the westernmost peak of Mount Trident and continues well up the slopes of

that mountain. This broken country is believed to be the surface expression of the course of the sill advancing from the Katmai conduit toward the Valley of Ten Thousand Smokes.

The Novarupta area has been the scene of intense and long-continued fumarolic activity. In 1919 Allen and Zies found very high temperatures here (1923, pp. 81, 104), and in 1923 certain vents a little to the northeast of Novarupta were still hot enough to melt zinc (419-C).

The strata of ash exposed in the fault scarps of Broken Mt. show varying intensity of explosive action. They contain a considerable variety of ejecta, but, viewed in the mass, there is an impression of sameness from one section to another. The multitude of intersecting faults and their large displacement make it difficult to compare sections. In general, the pumices are very coarse (a diameter of 1 to 2 feet is not unusual) and are of medium or light-gray color, but thick strata of dark brown or nearly black pumices occur, together with the ubiquitous black-and-white variegated pumices that give their unfailing testimony of the manner in which hybridization was effected. Blocks and fragments of andesites and shales are numerous in places and may attain 2 feet in diameter. They occur also inclosed in blocks of black obsidian. These obsidians with or without xenoliths, and in blocks and fragments of various sizes, are common constituents of the ash. A related material resembles bread-crust bombs, but is in irregular masses, up to 8 feet in greatest dimension. One of these is illustrated in plate 4, figure 1. They have an outer crust of black glass, much cracked, and the inner glass has been forced into the cracks. The interior may be of light-colored pumice, variegated pumice, or semi-pumiceous glass. It often contains inclusions of sediments, andesites, basic phenocrysts, pieces of pumice, and fragments of obsidian. In the background of the photo the ground is littered with these ejected masses. These "bombs" and the blocks of obsidian are believed to have been parts of a rigid or semi-rigid crust on the surface of the lava pool, formed during quiescent periods and ejected when activity was renewed. During the final uplift of the Novarupta dome a similar combination of rigidity and plasticity of the lava prevailed (Fenner, 1920, p. 590; 1923, p. 63).

Toward the end of the second (explosive) stage of Novarupta's activity the ejective force became so weak that the

ejecta were barely thrown clear of the crater. A surrounding wall or "corona" was built up. On the west this reaches a height of 200 feet above the general level outside. On the south and east the height increases, and on the north the corona merges with the gouged-out cliff of Broken Mt. Between the corona and the dome is a partly filled moat.

The ejecta in the corona show that with the weakening of the physical forces chemical action also became weak. Assimilation of xenoliths in mild form and welling-up of magma continued, but turbulence had nearly ceased.

Most of the ejected material of this stage is pumice in large lumps but there are also pieces of shale and sandstone and of dense andesite. Blocks of glass are numerous. Much of the pumice is variegated, and reproduces in pumiceous form the banded structure of the dome. It also shows the identical fractures that the variegated pumices of the incandescent tuff-flows and of the ashfall show wherever found. Successive stages of decreasing activity connect the violently ejected variegated pumices with the slowly upheaved banded rock of the dome.

Most of the pumice in the moat is inflated in a normal manner, but some specimens are of intermediate cellular structure between inflated pumices and the very slightly cellular glasses of the dome.

Novarupta differs from the many other vents that were sources of the incandescent tuff of the Valley in being of larger size, in having passed through a much more violently explosive stage, and in that its activity continued into a phase not represented elsewhere by which a dome of viscous lava was extruded. In this third stage assimilation and violent ejection had wholly ceased, but the cessation had been so gradual that much foreign material in various stages of digestion were still present in the stiffening magma, and the whole mass was slowly pushed up by continued accessions of magma from below. As it rose it congealed to a glass, but the upward thrust shattered a great portion of it. Much of the shattered material remained in approximately its relative position, but many blocks dropped into the encircling moat.

The banding gives direct evidence of the mechanism of extrusion of the dome. It is visible around the outer circumference, where masses of rock in place protrude through the disrupted blocks, and the direction of the banding is parallel with the cir-

cular outline of the dome. As the central mass was pushed upward the outer layers were overturned.

In 1919, studies of Novarupta were not carried as far as was desirable before the lateness of the season brought field work to a close. One of the principal objectives in 1923 was to continue these studies in minute detail, as Novarupta provided proof in visual form and on a large scale of the processes of assimilation.

The banding of the dome is expressed in alternations of rhyolite glass, free of phenocrysts except a very little quartz and sodic feldspar, with dark brown or nearly black scoria and glass containing large quantities of mafic phenocrysts. Here are exposed the processes of solution and assimilation by which the mafic pumices and variegated pumices of the Katmai region have been formed.

It is unfortunate that Novarupta is situated in such an almost inaccessible region. Except for its great size it would serve admirably as a museum model, and I believe that if it were available for general study there would be a radical revision of some of the commonly accepted theories of igneous processes. Certainly the introduction of some new thought is needed. The insistence by prominent geologists that all igneous theory must conform to the tenets of crystal fractionation has been stultifying to independence of thought and has delayed for many years progress toward an understanding of magmas and their processes.

In Novarupta an unusual set of circumstances has caused an outbreak of sialic magma highly charged with volatiles capable of exothermic reactions in the midst of detrital accumulations of basic lavas. After a certain amount of assimilation had taken place the process had been halted at just the right stage for critical examination.

In plate 4, figure 2 is shown a characteristic specimen of the banded lava. The point of the pick is near a scoriaceous xenolith, and a number of other xenoliths, both scoriaceous and relatively unaltered, are present. (Other examples of the banded lavas of Novarupta are illustrated in Fenner, 1923, pp. 54, 63; 1926, p. 741; 1944, p. 1085.)

Some of the basic xenoliths are angular and solid and have porphyritic texture. Others are rounded and have become somewhat scoriaceous, though porphyritic texture has not been

lost. Others have become scoriaceous masses from which brown bands trail off. Finally the last indication that the brown bands originate from the xenoliths appears as lenticular swellings.

I estimated that the brown, basic bands form one-third to one-fifth of the quantity of the rhyolitic bands. At the top of the dome (the core of the uplifted mass) the proportion of rhyolite is larger.

In speaking of basic bands the lenses and knots and little-altered xenoliths of andesite are included. They make up a considerable percentage of the basic material.

Generally, the inclusions are obviously basic rocks; occasionally shale or sandstone is found but is rather rare. Limestone has not been observed.

Phenomena of softening and digestion are numerous and plain. They show all stages of transition from distinct xenoliths of basic rocks (generally angular, sometimes rounded, often irregular in a minor way), through those that have become scoriaceous on the periphery and have mingled with the rhyolite; and those that have become scoriaceous throughout and whose melted-off particles have floated away from the parent mass; to knot-like clots of scoria lying along bands of mafic material; and finally to a system of parallel or sub-parallel mafic bands. Though individual bands may be many feet long, each finally tapers off in the all-inclusive rhyolite.

Examples of any of these stages may be found in hundreds or thousands. They are met everywhere in all the rocks of the dome, and the phenomena are so clear that it does not seem possible to suggest any interpretation but that the brown, basic bands that form so large a part of the rock of the dome have been produced by the melting and incorporation of masses of basic rock (with some sediments) which have become involved in the siliceous magma. Nothing hints at any other interpretation.

Though the rhyolite glass is much preponderant over the basic material, small portions of the latter have become so thoroughly disseminated that it is hard to get specimens of the rhyolite that are perfectly free of contamination; nevertheless there is no difficulty in finding large masses in which the amount of contamination is very small, and when the pure glass is analyzed it has exactly the composition of the uncontaminated rhyolite of the eruption in all its phases.

Plate 3. Exposure typical of basic phase of incandescent tuff-flow of Valley of Ten Thousand Smokes.

FIGURE 1

FIGURE 2

The maximum size of unaltered or nearly unaltered xenoliths is seldom more than 8 to 10 in., but some scoriaceous masses are much larger.

COMPARISON WITH VOLCANIC OBSERVATIONS BY OTHERS

Perret was undoubtedly the most indefatigable modern observer of volcanic eruptions. He has written as follows regarding the eruptions of Mount Pelée in 1929-1932, which he studied at close range (1935, p. 88):

"Many regard the liberation of steam resulting from crystallization as the actual cause (of explosions), but observation shows that a rise in temperature precedes the more intense Peléean eruptions while a similar change may be reasonably assumed to precede the lesser manifestations. Heilprin, who was near the summit of the mountain some four hours before the great explosion of August 30 (1902), describes the dome as 'boiling from all its parts, while the roar of escaping steam was appalling,' 'sublime and terrifying.' The photograph, Plate XX of his book, pictures the condition better than any words can do; in it the volcanologist sees the entire mass of lava rapidly heated by countless steam columns rising from underground conduits; conceives of exothermic reactions in the powerfully circulated liquid brought up from the interior of the volcano; and foresees the eventual attainment of a critical condition where the combined energy of the superheated vesicles shall exceed the resistance and the whole grand mass shall explode with cataclysmic violence. Cooling is not a factor in this great combination of causes, the total energy continues to rise."

Perret repeatedly emphasized the *auto-explosivity* of the lava in Peléean eruptions. The lava is not expelled as an inert mass by explosive energy from an external source, "it is the lava itself which explodes" (*op. cit.*, p. 86); and "gas discharge is a process characteristic of the entire mass of discharged lava and continues throughout its course after it leaves the crater" (*op. cit.*, p. 45).

In these excerpts Perret's conception is in close accord with that which I expressed in my papers of 1920 and 1923.

J. W. Judd, studying the effects of the famed eruption of

Plate 4.

Fig. 1. Ejected block from Novarupta.

Fig. 2. Alternation of siliceous and basic bands, Novarupta.

Krakatoa in 1883 (1888, pp. 1-46) had a less clear idea than Perret of the self-explosive properties of magmas, and the manner in which they become manifest. That is not surprising in the state of knowledge of sixty years ago, but his explanation of events seems to be still accepted. He recognized and even emphasized this self-explosive property, but he evidently had great difficulty in understanding in what way an explosion, once started, was brought to a stop while there was still explosive magma at hand. He proposed a mechanism that was physically impossible, but which has been often quoted with apparent approval.

Krakatoa, after preliminary symptoms, seems to have begun actual eruptions from an open vent on May 20 or 21. Booming noises were heard, ashes were ejected, and a steam column was seen. On May 27 an excursion party from Batavia found that the cone Perboewatan was active, "explosions occurring at intervals of 5-10 minutes, and each explosion being attended with the uncovering of the liquid lava in the vent." (Note the agreement with what has been deduced for Katmai). The cavity was about 150 ft. in diameter. A decline of activity followed, but no intermission. Then, from August 11 to the final culmination a heavy ejection of pumice and constant loud explosions were reported. From August 26 to 28 the eruption was in a paroxysmal stage. Even then the discharge was not continuous but took the form of distinct explosions. These were heard 1500 to 2000 miles (2500 to 3200 km.) away.

On August 27 a series of tremendous explosions occurred. There were four principal ones, of which the third was of surpassing magnitude. Judd's interpretation is that by these a breach in the crater walls was made, by which the sea gained access, and the effect of the inrush of cold water was like that of fastening down the safety-valve of a steam boiler. It "caused *a check and then a rally of* the pent-up forces of gases seeking to escape from the molten mass. The serious catastrophic outbursts that produced such startling effects in the air and in the ocean appear to me to have been the direct consequences of the 'check and rally' of the subterranean forces." (*op. cit.*, p. 25).

Verbeek estimated that during this phase some of the coarser fragments were thrown to a height of 164,000 ft. (about 31 miles or 50 km.). Fine dust (films of glass) remained suspended in the upper atmosphere for several years.

Judd's explanation will hardly stand analysis. An obvious objection is that the eruption was pre-eminently of a spasmodically explosive character almost from the first, and during this early period no such restraints as he invokes were present. Moreover, eruptions of other volcanoes (*e.g.*, Katmai) had this same spasmodic character though there was no water at hand to quench them. In Krakatoa (and other volcanoes) each of the violent explosions came to a termination of itself, for the sea certainly could not have gained access while the explosion was continuing in full force.

Evidently Judd did not realize the great thickness of crust that would have been required to restrain the enormous pressures. On what seem to be reasonable assumptions I have calculated that a plate of steel, of a tensile strength of 80,000 pounds per square inch, would have to be 90 to 100 ft. thick to withstand such pressure. A crust of unfissured glass would have had to be 200 ft. thick. It seems out of the question that any such crust could have been formed in the short intervals between explosions.

Although Judd realized that the explosive force resided in the magma itself he did not recognize that this force might not manifest itself immediately unless there was a physical restraint. Probably the fundamental problem that seemed to Judd to require explanation, and that is at the bottom of other explanations in which a restraining cover in one form or another is postulated, is to explain the spasmodic character of explosions, the "check and rally" of Judd. The difficulty arises, I believe, because the evolution of volatiles from a magma has been looked upon as a purely physical process (in the sense of the old distinction between physical and chemical forces) rather than as due to a series of chemical reactions. The phenomena of eruptions indicate that physical restraint is only part of the complex factors and that when an original restraint is removed chemical reactions follow but require time for development. When their chemical nature is realized the door is open for the recognition of a source of heat available for the assimilation of xenoliths and for other effects.

The idea that magmas have power of direct assimilation (much beyond anything contemplated in Bowen's reaction principle) is by no means new. It has been recognized and advocated by various competent geologists, but it has been rejected by a

greater number. The objections have evidently been influenced greatly by certain theoretical conceptions of the nature of magmas that are popular at present. An elaborate structure has been built up on these theories, and recognition of the ability of a rhyolite to incorporate and digest large amounts of basic rock would undermine the foundations of the structure and cause it to collapse. Consequently such ideas have been strenuously opposed. None the less, the evidence that the Katmai magma had this ability is too clear and definite to be brushed aside or argued out of existence. Primarily this conclusion is not based upon the petrographic and chemical evidence or the theoretical principles presented in this article, but upon field evidence so plain that no geologist could miss it. Laboratory investigations have supported this visual evidence, made it more definite, given it quantitative values, localized the site of heat development and assimilation in the upper part of the lava column, and provided a key to explain the formation of the great caldera of Katmai. The phenomena of the incandescent tuff-flow in the Valley of Ten Thousand Smokes and those of Novarupta provide additional information. All the results are in perfect accord with each other.

If, under proper conditions, magmas may exhibit great heat reserves and powers of assimilation, as I believe the Katmai phenomena have made certain, the implications are far-reaching and fundamental. Shifts of internal chemical equilibrium resulting from unloading may be brought into play at different rates —very slowly, as in the intrusion of stocks and batholiths, or with moderate or great rapidity, as in volcanic eruptions. The total heat output will not be affected by the time taken (except to a minor degree), but the effects upon the environment will vary greatly.

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THE FOX CLAY DEPOSIT, UTAH

BRONSON STRINGHAM AND BYRON J. SHARP

ABSTRACT. The Fox Clay deposit is located about 40 miles southwest of Salt Lake City. The clay occurs as a sedimentary lens. Tertiary (?) limestones which lie conformably below and above this bed, dip gently to the southwest. Flat-lying Tertiary basalt flows overlie the southern half of the area.

Differential thermal analysis indicates that the Fox Clay contains more water than typical halloysite $2H_2O$. Indices and differential thermal analysis curves vary with the degrees of hydration of the mineral. X-ray powder pictures, however, are constant regardless of degree of hydration, and compare favorably with powder pictures of authentic halloysite. The Fox Clay halloysite therefore contains adsorbed water which so affects all properties other than X-ray as to make it appear to be endellite $4H_2O$.

INTRODUCTION

A LARGE clay deposit, locally known as the Fox Clay, situated in the Lake Mountains, Utah, has been mined intermittently for several years. It contains one of the largest potential clay sources so far discovered in Utah, but the clay seriously shrinks and cracks on firing, making its industrial use, without treatment, impractical. It is located about 15 miles west of Provo on the lower southwestern rolling slopes of the Lake Mountains (fig. 1). The maximum relief within the area does not exceed 500 feet and the annual rainfall amounts to about 10 inches.

GENERAL GEOLOGY

The Lake Mountains constitute a north-south trending, typical Basin Range bordered on either side by broad alluvial-filled valleys. The rock units exposed consist of (a) Paleozoic rocks in the Lake Mountains proper, (b) a sequence of Tertiary (?) sediments and volcanic flows on the south-west flank of the range, and (c) Quaternary alluvium and lake sediments in the adjoining valleys. The Fox Clay is interbedded with the Tertiary (?) sedimentary rocks.

The Paleozoic rocks have been folded into a broad syncline with an axis trending northwest, oblique to the mountain range. The Tertiary (?) rocks are only gently folded and though no contact was found, are believed to rest unconformably on the Paleozoic beds on the lower flanks of the mountain.

STRATIGRAPHY

The oldest rock unit mapped in the area shown in figure 2 is a limestone presumably of Tertiary age. Due to the overlap

of valley alluvium, the lower contact of this formation was not found and its full thickness, therefore, is not known, but at least 100 feet of it is exposed. The rock is a fine-grained, dense, tan, unfossiliferous limestone which weathers pale bluish. Microscopic examination shows it to be composed of an aggregate of calcite with an average grain size of about 0.25 mm. Oolites, ranging in diameter from 0.1 to 0.3 mm. are found in scattered patches throughout the aggregate.

The Fox Clay bed overlies the lower limestone conformably and occurs as a lenticular bed with a maximum thickness of 18 feet at the main excavation near the center of the mapped area (fig. 2). It thins rapidly to the south and east, while to the northwest the thickness is not determinable since the outcrop is there covered by valley alluvium.

The bedding in the white clay is expressed by faint pink to brown laminations and banding. Locally, the upper part of the

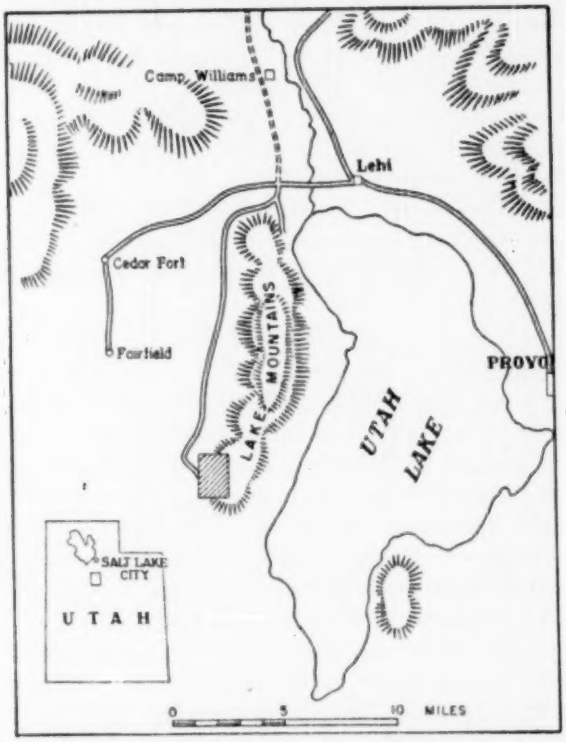


Figure 1. Index map showing the location of the Fox Clay deposit, Utah.

bed is stained by concentrations of hematite in broad pink to maroon bands which make an acute angle with the bedding laminations, giving it a false appearance of crossbedding. The clay is contaminated with varying amounts of detrital quartz, and in the central part of the area near the excavations it contains angular quartz grains up to 5 per cent, while near the borders 15 per cent of quartz in rounded grains is noted locally. A limestone which is identical lithologically to the lower limestone overlies the Fox Clay bed conformably and overlies the lower limestone where the clay lenses out.

A basalt flow overlies these Tertiary (?) sediments with moderate angular unconformity. It rests directly on upper limestone, Fox Clay, and lower limestone in different parts of the area. The flow is about 50 feet thick and caps some higher hills to the south.

STRUCTURE

As stated above, the Tertiary (?) sedimentary rocks are all conformable with each other and maintain a general dip to the southwest of 5° or less. The beds dip locally as high as 40° on two small anticlines whose axes trend north 30° west. These folds disappear under the alluvium to the northwest and die out toward the southeast.

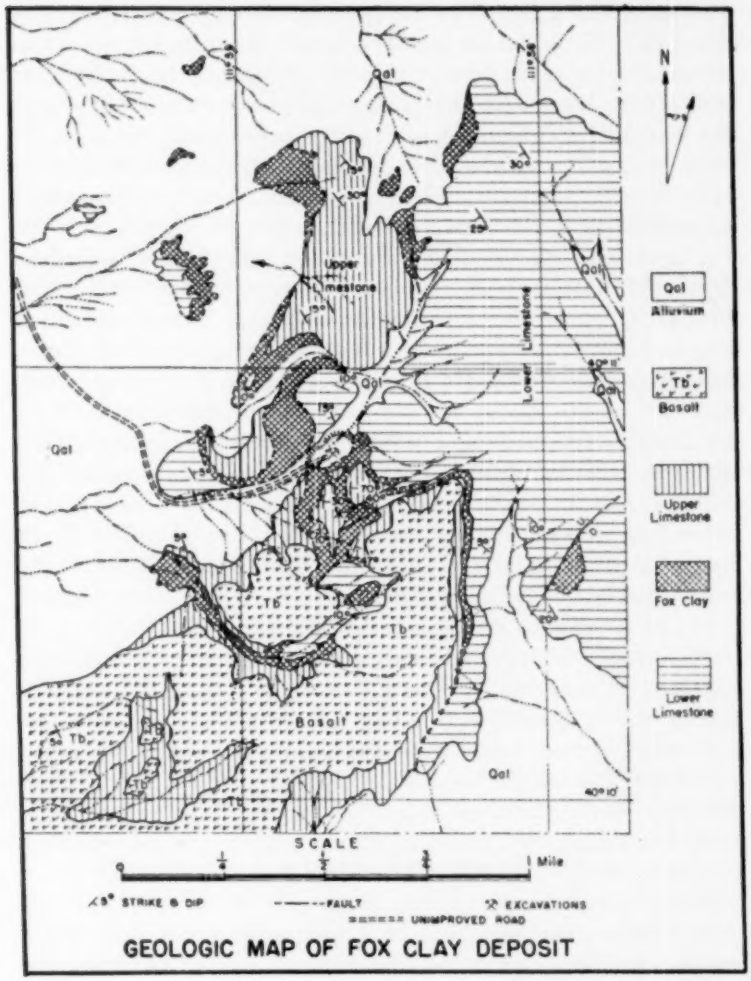
Three faults displace the clay bed. Two of these which are found southwest of the main excavation are parallel and strike north 65° east, with a total displacement of approximately 200 feet.

AGE OF THE CLAY

No fossils of any kind were found within the entire area mapped; hence only an estimate can be made as to the age of these rocks. They have been tentatively assigned to the early Tertiary because of their unconformable relationships to the underlying Paleozoic rocks which presumably were deformed during the Laramide movements. The limestones and clay beds themselves are folded to an extent comparable to that of the Flagstaff limestone of Eocene age in the Central Utah area described by Spieker (1946, pp. 136-137). The Fox Clay is definitely older than the undeformed overlying basalt which is probably the same age as the late Eocene or Oligocene basalts north of the Lake Mountains described by Gilluly (1932, p. 66).

MINERALOGY

Through the kindness of Sterling B. Hendricks of the Bureau of Plant Industry, U. S. Department of Agriculture, a fresh sample of authentic endellite $4H_2O$ from Lawrence County, Indiana, was obtained for purposes of comparison with Fox Clay. Mineralogical examinations, therefore, were made on fresh endellite $4H_2O$ (sample A), dehydrated endellite (sample B), obtained by allowing ground-up fresh endellite to dehydrate at room temperature for 48 hours, untreated Fox Clay



GEOLOGIC MAP OF FOX CLAY DEPOSIT

(sample C), and dehydrated Fox Clay (sample D), obtained by allowing ground-up material to dehydrate at room temperature for 72 hours. Examination of these samples by X-ray, differential thermal analysis, electron microscopic and optical methods yielded sufficient information to establish the mineralogy of the Fox Clay.

X-ray Investigations.—Debye-Scherrer diffraction pictures were taken of all of the different samples. Pictures of dehydrated endellite (sample B), untreated Fox Clay (sample C), and dehydrated Fox Clay (sample D), showed lines essentially identical. The *d* values and intensities of the line patterns of these samples are nearly equal to the *d* values given for halloysite $2H_2O$ (Nagelschmidt, 1934, p. 131, table V, no. III) except for line number 1 which shows a value considerably less than the value given by Nagelschmidt. If this figure had been greater than Nagelschmidt's there would have been reason to think that some excess water for halloysite $2H_2O$ was still present between the layers; however, the lower figure for hydrated Fox Clay halloysite $2H_2O$ and its similarity to dehydrated authentic endellite $4H_2O$, seems to point out clearly that this mineral has the true structure of halloysite $2H_2O$ regardless of degree of hydration. Authentic endellite (sample A) was ground, mounted on the X-ray camera and a picture taken all within 50 minutes. This proved to be successful in producing a pattern different from halloysite $2H_2O$ and similar to that of endellite $4H_2O$ (table 1; A. S. T. M. index; and Mehmel, 1935). The information obtained thus establishes that the Fox Clay, both hydrated and dehydrated, is halloysite $2H_2O$ and that the excess water of the hydrated sample is simply adsorbed and does not occupy a position in the structure.

Differential Thermal Analysis Investigations.—Curves were obtained on a number of samples of the material investigated. Conventional apparatus for this determination was used, and the results thus obtained show the same curves for dehydrated endellite $2H_2O$ and for dehydrated Fox Clay. Both have a large definite endothermic peak at 600° C. and a smaller sharp exothermic peak at 980° C., corresponding very well to published curves for halloysite $2H_2O$ (Kerr and Kulp, 1948, p. 400).

In the curves for the hydrated samples of each clay the expected large endothermic peak between 100° and 200° C. is present and represents the expulsion of lattice water in the case of endellite $4H_2O$ and adsorbed water in the case of the

halloysite $2H_2O$ of the Fox Clay. Otherwise the curves are the same as for halloysite $2H_2O$.

Optics.—The immersion method of determining index of refraction was used on all specimens and the liquid employed was checked with an Abbé refractometer at the time the measurement was made, thus assuring a more accurate observation. The untreated Fox Clay (sample C), was found to be isotropic with an index of 1.543. In recent investigations by Alexander *et al.* (1943), the index of refraction of pure endellite $4H_2O$ was calculated as $1.49 \pm .005$. They indicate that the index of completely dehydrated endellite (halloysite $2H_2O$) may range as high as 1.556. All halloysites $2H_2O$ and endellites $4H_2O$, therefore, should fall between these extremes. The Fox Clay, with an index of 1.543, falls below the index of pure halloysite $2H_2O$. This anomaly is believed to be due to an envelope of water surrounding the halloysite grains as found by Alexander *et al.* (1943). The index of a dehydrated sample of Fox Clay was determined to be 1.556 as expected.

Electron Microscopic Observations.—Professor Tom F. Bates of Pennsylvania State University was kind enough to take an electron micrograph of the Fox Clay. The picture shows that the clay is made up of the tube-shaped particles typical of halloysite $2H_2O$.

Mineralogical Conclusions.—From the above data, it seems clear that the mineral composing the Fox Clay is halloysite $2H_2O$ and that the extra water is simply adsorbed water present interstitially and surrounding the grains. MacEwan (1947) presumes that naturally occurring halloysites may be intermediate in water content between true halloysite $2H_2O$ and true endellite $4H_2O$, and proposes a terminology based upon this concept. The results of this study support the view, however, that there are two separate and distinct minerals existing, *i. e.*, halloysite $2H_2O$ and endellite $4H_2O$, that there is not an isomorphous or continuous series between the two, and that what appears to be hydrous halloysite is nothing more than true halloysite $2H_2O$ with adsorbed water and this condition causes the index of refraction and differential thermal curves to simulate those of true endellite $4H_2O$. The nomenclature of Alexander *et al.* (1943), in using only the two terms endellite and halloysite therefore is preferred.

ORIGIN

The Fox Clay occurs between two sedimentary beds and

lenses out within the small area studied. It contains clastic quartz grains in varying amounts and no evidence of volcanic ash is observed. The clay must therefore be sedimentary in origin. It is believed that the original material was formed as endellite and was derived through the process of weathering. This was finally transported and deposited as clastic material in the clay bed along with some quartz grains. It is believed that during transportation dehydration was effected, changing the endellite to halloysite. The hydrated condition now existing is presumed to be the result of saturation at the time of deposition or through subsequent ground water activity.

ACKNOWLEDGMENTS

Appreciation is offered to the University of Utah Research Fund for supplying the differential thermal analysis equipment.

TABLE 1

Line Number	Endellite $4H_2O$ Indiana Sample A d	I/I_1	Endellite $4H_2O$ Mehmel (1935) d	I/I_1	Endellite $4H_2O$ Dehydrated to Halloysite $2H_2O$ Indiana Sample B d	I/I_1	Halloysite $2H_2O$ Fresh, hydrated* Fox Clay Sample C d	I/I_1	Halloysite $2H_2O$ Upper Silesia Nagelschmidt (1934) d	I/I_1
1	10.08	1.0	10.1	1.0	7.28	.8	7.24	.7	7.43	.6
2	4.36	.8	4.46	.8	4.40	1.0	4.40	1.0	4.44	1.0
3	3.31		3.40	.6	3.61		3.54		3.61	.8
4	2.54		2.56	.6	2.56		2.53		2.57	.8
5	2.42				2.43		2.45			
6	2.36		2.37	.5	2.36		2.31		2.36	.8
7	2.21		2.23		2.20		2.25		2.23	.2
8	2.14				2.14					
9					2.06					
10	2.01				2.02				2.01	.4
11	1.97				1.96		1.96			
12	1.90				1.90					
13	1.77				1.78		1.77			
14	1.73				1.73				1.71	
15	1.66		1.67	.5	1.67		1.67		1.63	.8
16	1.62				1.62					
17	1.46	.7	1.48	.6	1.47	.9	1.47	.8	1.47	1.0
18	1.44				1.44					
19	1.27		1.28	.6	1.27		1.27		1.29	.8
20	1.22		1.23	.4	1.22		1.22		1.23	.6

* Dehydrated Fox Clay (Sample D) shows same lines and intensities as sample C.

Intensity figure given only to three most intense lines in samples A, B, and C.

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SANDSTONE SPINDLES*

K. M. HUSSEY AND B. A. TATOR

ABSTRACT. Sandstone spindles, a peculiar feature of weathering, are found in restricted areas of the Dawson arkose (Eocene) outcrop at Corral Bluffs near Colorado Springs, Colorado. These are relatively small, spindle-shaped structures occurring in closely spaced, parallel arrangement in the surface of the exposure. They result from decementing activity by ground-water solutions which develop zones of weakness along planes of cross-bedding and jointing. Removal of the material made friable in this manner leaves the more firmly cemented portions as spindle-shaped protuberances in the face of the outcrop.

INTRODUCTION

SEVERAL years ago the attention of the writers was attracted to certain spindle-shaped features of weathering in the Dawson arkose beds (Eocene) at the site of the Corral Bluffs east of Colorado Springs, Colorado (fig. 1). These odd-shaped bodies seem to answer a description by Cotton (1942, p. 32, fig. 37) of "earth fingers" produced by wind abrasion. Detailed study of the occurrence and composition of the Colorado specimens, however, leads to the belief that the wind was not more than a contributing factor in their formation. The term "sandstone spindle" is proposed for them and the results of the study of their composition, occurrence and development are presented.

About nine miles east of Colorado Springs, Colorado, a very prominent southwest-facing escarpment, locally known as Corral Bluffs (fig. 1), has been formed by the headward erosion of a number of minor intermittent streams in the Dawson arkose.

The area has a distinctly semi-arid climate, the major part of the average annual rainfall of 14 inches being received as a series of violent local showers during the summer months. The prevailing wind direction (fig. 1) is from the southeast (U. S. Weather Bureau, 1946), changing to north during the winter months. The area in which the sandstone spindles occur is entirely devoid of soil or vegetation.

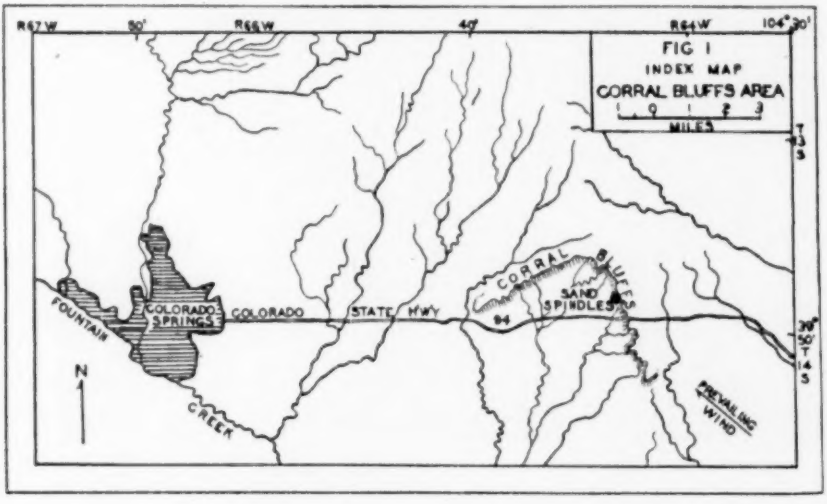
The beds exposed in the Corral Bluffs belong to the upper portion of the Dawson as described by Dane and Pierce (1936), consisting of interbedded layers and lenses of fine- to coarse-grained arkose, conglomeratic arkose, and sandy, carbonaceous

* Iowa State College and Louisiana State University Geology Camps Research Paper No. 6.

shale. The material is extremely friable, often crumbling at the touch.

The Dawson strata are essentially horizontal, though there is a regional dip of a few degrees to the southeast. The lowermost beds exposed, consisting of medium-grained, well-cemented arkose, have indeterminate thickness since they lie at the base of the escarpment. Overlying these beds is a sandy, carbonaceous shale 80 feet thick. A 15-foot layer of coarse-grained conglomeratic arkose overlies the shale, forming a bench about 100 feet above the base of the bluff. This in turn is overlain by a 6-foot layer of coarse conglomeratic arkose which, with additional beds of no importance to this writing, forms the upper part of the escarpment. All layers in this section, particularly the coarser arkoses, are strongly crossbedded. The sandstone spindles are in the upper and lowermost beds exposed.

Two sets of joints are present with relationship about normal to the bedding. These two sets, however, are not expressed with equal persistence in the same portions of the outcrop, one or the other usually being more prominent. The more pronounced set has a northwest-southeast trend; the other strikes approximately northeast-southwest. The spacing between joints varies from a few inches to several feet. The best development of the joints is in the coarser-grained



arkose beds, none being discernible in the thick shale beds in the section.

A relationship between jointing and friability of the exposed rock surface is apparent. Prominent, narrow, wall-like ridges, projecting several inches to as much as one foot above the surface of the outcrop, occupy many of the interjoint areas. These extend for as much as 8 or 10 feet laterally or vertically in the exposure. Some of them have partially developed sandstone spindles along their sides.

SANDSTONE SPINDLES

Shape and Size.—The spindles are elongate rounded cylinders composed of the same clastic material as the enclosing formation (plate 1, fig. 1). The ends are somewhat tapered in some and bluntly rounded in others, the average overall appearance being that of a spindle. The range in size is from small finger-like features about one inch in length by ¼ inch in diameter, to a maximum of 2 feet in length by over 2 inches in diameter.

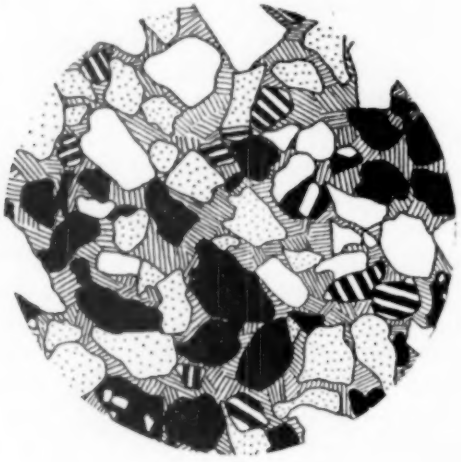


Figure 2

PLATE 1

Fig. 1. View of a west-facing slope of the Dawson arkose outcrop in Corral Bluffs. Note the horizontal and vertical alignment of the sandstone spindles.

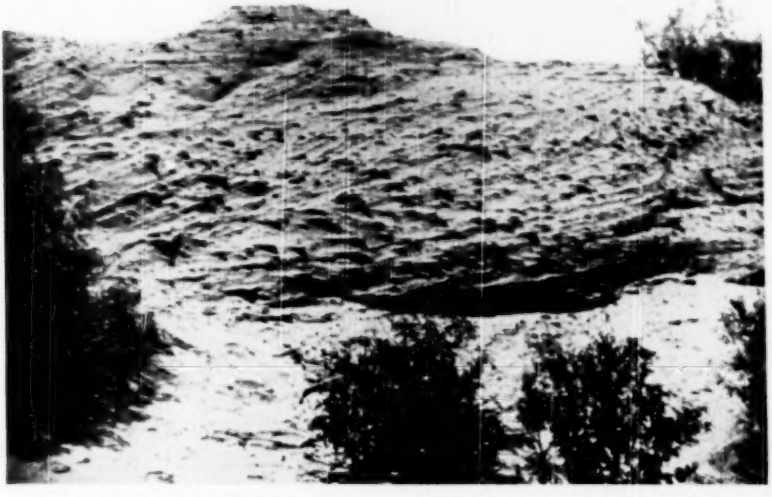


Fig. 2. View showing the crossbedded character of the Dawson arkose. The sandstone spindles show a definite alignment with the crossbedding.

Composition.—There is no detectable compositional difference between the spindles and the enclosing formation except perhaps in degree of cementation. Microscopic study (fig. 2) of the material reveals it to be composed of approximately 25 per cent quartz, 15 per cent potash feldspar, 5 per cent plagioclase feldspar, 25 per cent unidentified opaque grains, and 30 per cent gypsum in the form of cement. The grains range from fine sand size to granule particles up to 5 mm. in diameter. The feldspar fragments comprise most of the angular to subangular grains, whereas the quartz and opaque particles are subangular to subrounded. The gypsum cementing material is crystalline, orientation of the crystals being about as shown in figure 2. Most of the grains are coated with a thin layer of iron oxide. Petrographic[1] as well as magascopic study shows this material to be concentrated in the more friable, obviously weathered areas peripheral to the spindles. The varied size and shape of the fragments allows for a close packing of the grains. Almost all of the space between the grains is occupied by the gypsum cement, which thus materially reduces the porosity and makes all but the bedding-plane and joint-plane areas relatively impermeable to water. The only difference in composition is found in the more friable zone surrounding each spindle; there the cementing material is less abundant.

Occurrence.—The sandstone spindles are present in all degrees of completeness on the surface of the outcrop. Some are lying free, completely weathered out, whereas others are not more than faint outlines. In most instances excavation of the partially exposed specimens failed to obtain a complete form. They seem to be solely the product of weathering; below the shallow weathered zone it is not possible to detect even a trace of a spindle.

These features are present only at the southeastern end of the Corral Bluffs (fig. 1) in the medium- to coarse-grained arkosic horizons of the section. Their finest development is on a westward-projecting spur in the top of the cliffed portion of the section about one-quarter mile north of State Highway 94. Poorer specimens are found, however, in the finer-grained arkose about 100 feet lower in the exposure in a creek bed a short distance from the base of the cliff. Additional, scattered, poorly formed examples occur about 50 yards north of the

[1] Petrographic analysis by C. J. Roy, Iowa State College.

above-mentioned spur in a coarse-grained, conglomeratic arkose directly overlying the spur-forming stratum.

Orientation.—The spindles have both a vertical and horizontal pattern of alignment. The vertical arrangement is associated with the joint systems mentioned earlier, whereas the horizontal pattern is directly related to the crossbedding.

These features also have the same general orientation, that is, they are roughly parallel, in any one locality. However, in the four separate places of occurrence noted, two main directions of longitudinal alignment prevail. In the coarse arkose layer outcropping on the spur top in the upper portion of the bluff, the trend is N. 75° W., being coincident in direction with the more prominent of the two joint sets mentioned earlier. In the medium-grained arkose which directly overlies the latter bed, and at a locality some 50 yards to the north, the orientation is N. 50° E. In the coarse arkose layer underlying the thick shale bed the trend is N. 75° E., whereas in the outcrop of the same layer in the creek bed a short distance west of the cliff base the orientation is N. 30° W. In the latter occurrence the spindles show a streamlining in the downstream direction, and are apparently molded at least in part by stream action.

MODE OF DEVELOPMENT

General.—A number of possibilities for the origin of the sandstone spindles have been examined by the writers. Analysis reveals that they are neither concretionary in the true sense nor of primary origin. No nucleus of foreign material, fossil or otherwise, is present in them. The texture is precisely the same in the areas between the spindles as within the features themselves, the only distinction being the better state of cementation in the latter. No trace of the spindles can be found in the unweathered arkose. Hence, they must be of secondary origin and the result of either additive or subtractive activity on the part of groundwater.

The possibility that wind abrasion has fashioned them must be excluded on two grounds. First, they occur in limited exposure protected by topography from the force of the prevailing southeasterly wind (fig. 1). Second, the orientation in two major directions within a very localized area makes it very improbable that the wind could etch the exposed rock surface in two different directions at the same time. Furthermore, lack

of occurrence of the forms in strata of widespread textural similarity, in many localities exposed to the full force of the prevailing wind, would seem to eliminate this agency as a primary cause of their development.

Similar-appearing features have been described by Barbour (1901) in outcrops of the Arikaree formation (Miocene) in Nebraska and South Dakota. However, he found that the controlling factor was a radiating growth of secondary calcite which, as a cementing agent, created true concretions. Petrographic analysis of the sandstone spindles proves that no such controlling secondary mineral growth is present.

Influence of Crossbedding.—The exposure containing the finest developed examples is strongly crossbedded. A decided alignment of the spindles with the crossbedding is apparent (plate 1, fig. 2). They occur in the thinly layered units between the bedding planes. It would appear then that the planes of contact between adjacent units of the crossbedding provide greater freedom for the movement of groundwater solutions which act as decementing agents. Under such circumstance the removal of cement would be an inward-progressing process in each of the crossbedded units (fig. 3). Thus the spindle alignment with these units in horizontal dimensions is explainable on the basis that these are areas from which the cement has not been removed.

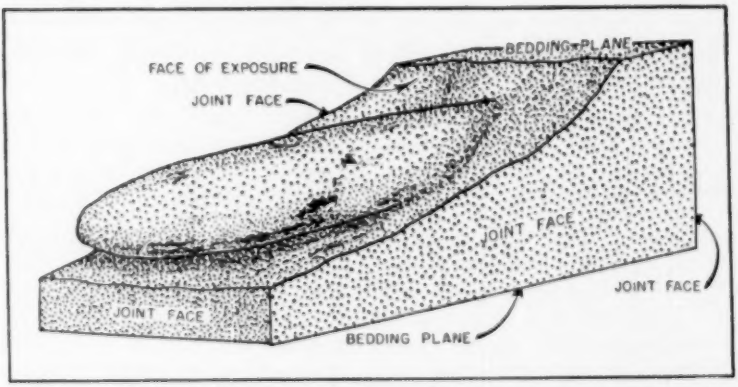


Fig. 3. Idealized diagram of a trapezohedral rock unit showing the means of development of a sandstone spindle by decementation. The joint faces and bedding planes provide ease of ingress for solutions which progress inward. The spindle is a residual core which still retains its cement. Differential weathering then leaves the feature as a projection from the face of the exposure.

Influence of Joints.—In the vertical dimension the two major joint systems noted earlier are the controlling factor in the location and the spacing of the spindles; the greater prominence of one set of joints determines the direction of elongation. The decementing activity of groundwater solutions along the joints has developed greater friability in zones roughly perpendicular to the crossbedding. Thus the sandstone spindle may be thought of as occupying the central portion of a trapezohedron, the length, breadth, and height of which is determined by the spacing of the joints and the thickness of the units of crossbedding. The trapezohedron is affected from all sides by solutions working inward from the surrounding zones of freer movement (fig. 3). Iron staining of the peripheral portions of the spindles tends to support this view, particularly since the stained areas are also more friable than the central portions. The decementing action undoubtedly involves a removal of the gypsum cement by percolating ground water. This leaves a zone of practically uncemented grains on five sides of the trapezohedron.

The projecting nature of the spindles in the exposure is the result of differential weathering. The more friable zones are worn back more rapidly than the relatively better-cemented areas; this action involves removal of the loosened clastic fragments from the surface of the exposure by rainwater and wind. The slower weathering of the more coherent centers of the trapezohedral units allows them to remain as spindle-shaped projections in the face of the exposure.

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COMMUNICATION

A *Geological Map of British Columbia* recently issued by the Geological Survey of Canada, with scale of one inch to twenty miles, illustrates the energy of a Survey which is responsible for a scientific treatment of 4,000,000 square miles or one-twelfth of the world's dry land. British Columbia alone is one-tenth of the Dominion. Although little more than one-fourth of this map bears designating colors for the exposed formations, it is eloquent of the inestimable amount of foot-slogging, perspiration on hob-nails, during the 75 years since George Mercer Dawson began his remarkable reconnaissance. A wild, rugged country, where rock outcrops are much diminished by almost continuous forest cover and where there is limited access by railways, dirt roads, and even horse-trails, is this scene of hard labor. Yet the devoted workers in the province have shown the intriguing quality of the geology of the 95,000 square miles actually colored—a total area six times that of the more accessible Switzerland.

On the present occasion only one outstanding feature of the map will be emphasized. It bears no color representing any definitely Archean or "Archeozoic" group of formations, and this in spite of gigantic upturnings and upthrustings of thick masses of the earth's crust. The oldest formations of the legend include the Purcell series and the unconformably overlying Windermere series, both referred to the "Proterozoic" and thus to be regarded as analogues of the Beltian or Algonkian. In contrast Dawson regarded the "Shuswap complex" of granites, gneisses, schists, pegmatites, aplites, marbles, and greenstones, occupying considerable areas west of the Selkirk Range, as a true Archean terrane from which were chiefly derived the main bulk of the voluminous Late pre-Cambrian and Cambrian clastic sediments of the province. The International boundary from the Great Plains to the Pacific nowhere crosses a typical and proved Archean assemblage, nor has any been found in Vancouver Island or the Queen Charlotte Islands. On the other hand, the present writer's 1911-1912 reconnaissance along the main line of the Canadian Pacific Railway from Kamloops to Golden appeared to corroborate Dawson's reference of the "Shuswap complex" to the Archean. The new evidence was derived near Albert Canyon station, where to the west a broad band of Shuswap rocks makes sharp contact with a thick mass of Beltian-Cambrian clastics extending all the way to the Great Plains. East of that contact the writer, after prolonged search, failed to find a single pegmatite or aplite dike or sill cutting the basal Beltian beds. This fact, coupled with microscopic study of the basal quartzite, suggested that here is a major unconformity (more specifically an arkose unconformity) between the two ter-

ranes. No other such evidence by unconformity seems to have been published.

After 1912 S. J. Schofield and other members of the Survey staff showed that the late-Mesozoic batholithic invasions of the province developed granite-gneiss-pegmatite-aplite complexes like that of the Shuswap terrane west of Albert Canyon station. In Part A of the Survey's Summary Report for 1928 H. C. Gunning reported his discovery that the Beltian sediments a few miles east of Albert Canyon station are cut by dikes of both pegmatite and aplite, and that only a short distance to the south is an outlier of a large late-Mesozoic batholith clearly intrusive into the Beltian series. He therefore concluded that the Albert Canyon contact is better explained as intrusive rather than as one of unconformity. To the present writer this deduction was long uncertain, since he saw no reason against assuming two epochs of granite-pegmatite-aplite eruption, one pre-Beltian and the other late Mesozoic. However, a recent study of Gunning's field data (further detailed in a personal letter of 1924 and also in his 1929 report on the "Big Bend Map-area") and of the relevant memoirs by other members of the Survey has led to the conclusion that, with a high degree of probability, Gunning was right in his judgment, and that all these explorations along the Cordilleran strike show the Albert Canyon "unconformity" to be illusory: that the adjacent "Shuswap" rocks are not to be referred to the Archean.

Sharing that opinion, the Survey men are conscious of a mystery: what was the chief dry-land source of the Proterozoic and Cambrian, clastic sediments of British Columbia? The same problem in the paleogeography of pre-Ordovician time is far from solution in the Cordilleran belts of both Yukon Territory on the north and the United States on the south.

It has been suggested from field evidence that most of those ancient sediments were not derived from the Archean shield of eastern Canada but did come from a broad terrane ranging along the Pacific side of the most westerly islands from Alaska to California. Such a land-mass, presumably sialic and capable of supplying the enormous volumes of quartzites and metargillites in the Beltian geosynclinal prisms, was imagined by C. Schuchert and named by him "Cascadia." A. J. Eardley (Am. Assoc. Petroleum Geologists Bull., 1949, vol. 33) accepts the same general idea but prefers to describe the parent terrane as a "Volcanic Belt." Neither of these conceptions of the parent terrane has been discussed in relation to the principle of isostasy. Neither terrane is now visible. The maps of Schuchert and Eardley show the place of the vanished terrane to have been largely taken by Pacific water approaching 12,000 feet in depth. Yet there is reason to believe that gravity is nearly normal along the same belt, now

offshore, and good reason for doubt that the sunken terrane could have had its density increased so much as to ensure near-isostasy after the supposed subsidence.

If, then, the bulk of the Proterozoic and younger clastic sediments of British Columbia be assumed to have "come from the west" —from a broad long-lived land of Archean rock situated west of the present outermost shore of the Pacific—some additional speculation is in order. Is it too fantastic to guess that that parent terrane became buried under North America when the western part of our existing continent slid over or was thrust over the simatic Pacific sector of the earth's crust?

REGINALD A. DALY

REVIEWS

Outlines of Biochemistry; by the late Ross Aiken Gortner. Revised by Samuel I. Aronovsky, Paul D. Boyer, David R. Briggs, Henry B. Bull, George O. Burr, William F. Geddes, Ross A. Gortner, Jr., Willis A. Gortner, W. M. Sandstrom, and J. J. Willaman; 3rd ed., edited by Ross Aiken Gortner. Pp. xv, 1078; 125 figs. New York, 1949 (John Wiley & Sons, Inc., $7.50).—This second revision of Gortner's Outline is a timely contribution to the field of biochemistry in which so many dramatic advances have been made during the past ten years. The new edition results from the efforts of the late Ross Gortner's two sons, Ross A. Gortner, Jr., and Willis A. Gortner, aided by a highly competent staff of eight collaborators. All of the latter were in some way associated in biochemistry with Gortner, Sr.

The book is unique in presenting, in a very comprehensive fashion, the organic chemistry and physical chemistry upon which biological phenomena are based. However, little attempt has been made, as in previous editions, to correlate the theory with the bulk of the descriptive material. No attempt is made to cover practical or clinical applications of biochemistry except for occasional illustrative purposes; for this reason, the approach is not of primary interest to a medical student. Rather, the book will be eminently useful to anyone desiring to keep abreast of recent developments in biochemistry through a rapid survey of the field.

In the new edition, there are revisions to nearly all the chapters, especially those on vitamins, protein metabolism and polysaccharides, and new sections on carbohydrate metabolism, lipid metabolism and protein denaturation have been added. The sections on colloids and carbohydrates are especially well organized and clearly written.

As was the case with previous editions, the book should be widely read and enjoyed. HARRY H. WASSERMAN

Selenium. Its geological occurrence and its biological effects in relation to botany, chemistry, agriculture, nutrition and medicine; by Sam F. Trelease and Orville A. Beath. Pp. x, 292; 66 figs. New York, 1949 (Published by the authors, Box 42, Schermerhorn Hall, Columbia University, $5.50).—Selenium is almost unique among the chemical elements occurring in toxic concentrations in the biosphere. It is accumulated by certain plants, notably of the genera *Astragalus*, *Xylorhiza* and *Oonopsis*, which if eaten continuously by livestock cause a serious, usually fatal, condition known as blind staggers. Selenium may also enter to wheat and grasses from richly seleniferous soils. When these plants are eaten the selenium produces a different pathological state, the so-called alkali disease; a condition comparable to alkali disease probably exists in

man. Trelease and Beath have produced an admirable monograph, of equal interest to the stockman and the geochemist, on the selenium cycle in nature in both its theoretical and applied aspects. The whole of the geochemical and botanical literature is considered. It is evident that the selenium problem is sufficiently well understood to enable intelligent control to be undertaken in the selenium belt that stretches north from New Mexico through Wyoming into Canada. There, however, is still an enormous amount of work to be done on the purely scientific aspects of the problem. The explanations of the localized occurrence of seleniferous sediments in various Cretaceous formations are unsatisfactory. Almost nothing is known of seleniferous sediments, soils, and plants outside North America. The physiology of the apparent need for selenium by certain species of *Astragalus* requires further investigation, and the study of the organic chemistry of the selenium present in accumulator plants has only just begun. If the authors succeed in stimulating further work on these problems they will be intellectually rewarded; since they have evidently had to take considerable risk in producing the book themselves, it is also to be hoped that they will be financially rewarded by many investigators purchasing their work.

G. EVELYN HUTCHINSON

Annual Reports on the Progress of Chemistry for 1948 (Volume 45); issued by THE CHEMICAL SOCIETY. Pp. 379. London, 1949 (£1.5.0).—This volume is written by 22 experts. It summarizes the progress in certain fields of chemistry during previous years; in some cases since earlier reviews. There are 21 articles collected under the headings of general and physical, inorganic, organic, and analytical chemistry and biochemistry. As one comes to expect of the Reports the writing is clear, scholarly, yet on the whole lively, so that reading is a pleasure. Workers in the field of the earth sciences might find particularly valuable the coherent view of chemical reactions induced by ionizing radiations, by F. S. Dainton. In the biochemistry section there is a thorough review of partition chromatography by A. J. P. Martin. The analytical section contains reviews of analytical emission spectrography; flame photometry; volumetric analysis; and analysis of sea water.

HAROLD G. CASSIDY

Artificial Radioactivity; by P. B. MOON. Pp. 102. New York, 1949 (Cambridge University Press, $2.50).—This is an authoritative monograph on its subject matter. It presents an outline of the main phenomena and techniques of radioactivity, focussing its emphasis upon recent developments in the study of light- and medium-weight radioactive nuclei. Their variety is so great that com-

plete coverage of the field in so small a volume is impossible. But the book is most useful because of the significance of the examples chosen for treatment and because of its references to the current literature. It provides a survey rather than an explanatory text.

HENRY MARGENAU

Excited States of Nuclei; by S. DEVONS. Pp. 152. New York, 1949 (Cambridge University Press, $2.50).—Nuclear spectroscopy is rapidly becoming a subject of enormous complexity, largely unrelieved at present by the attempts of theorists to unravel its complications. Accordingly, the monograph under review is mainly an empirical account of a vast body of information, collected in 4 chapters which deal, successively, with excitation of bound nuclear states, excitation of virtual states, radiative transitions and interpretations. All discussions are up to date. And while the author confers his principal emphasis upon experimental methods, he nevertheless succeeds in providing as complete and satisfactory a picture of the theoretical situation as skill and good judgment can supply.

HENRY MARGENAU

A General Kinetic Theory of Liquids; by M. BORN and H. S. GREEN. Pp. 98. New York, 1950 (Cambridge University Press, $2.25).—Six important papers, published by the authors in the Proceedings of the Royal Society A, are collected and issued in book form. They deal with general questions of the kinetic theory, the quantum mechanics of fluids, and culminate in an application of the new theory to liquid helium.

HENRY MARGENAU

Introduction to Theoretical and Experimental Optics; by JOSEPH VALASEK. Pp. x, 454. New York, 1949, (John Wiley & Sons, Inc., $6.50). This is not only a general text covering all the usual topics in optics and spectroscopy, but it will also serve excellently as a fairly elementary and up-to-date reference book in applied optics and optical egineering. Only a course in general physics and one in the calculus are assumed as background. The book is divided into four parts: geometrical optics, physical optics, radiation and spectra, and experimental optics. There are twenty-four experiments, including three with x-rays, plus a section on the photographic process, in this last part. X-rays, photographic optics and ophthalmic lenses, three specialties of the author, are treated in more detail than usual in optics texts.

There are a number of problems applying the theory at the end of each chapter. Although the consideration of topics in modern optics seems complete, some developments such as colorimetry are treated in rather cursory fashion. References are always included,

however, and the discussions are accurate as far as they go. This book is highly recommended as an optics text at the intermediate level and as a useful reference source on optical problems encountered by specialists in other fields. W. W. WATSON

Vacuum Equipment and Techniques; by A. GUTHRIE and R. K. WAKERLING, editors. Div. 1—Vol. 1 of National Nuclear Energy Series. Pp. xvii, 264. New York, 1949 (McGraw-Hill Book Co., Inc., $2.50). This volume is one of about sixty now being published in the National Nuclear Energy Series as a result of the huge amount of scientific and technical research and development done under the auspices of the Manhattan District during the war. It gives the observations made in the high-vacuum program at the University of California Radiation Laboratory. The large-scale equipment built according to the designs resulting from this research program was an important contribution to the success of the electromagnetic separation plants at Oak Ridge.

In a rather lengthy Chapter 1 R. Loevinger gives an excellent account of those parts of the kinetic theory of gases that are useful in modern vacuum practice. Another feature improving this as a reference work is a set of appendices giving all the necessary formulas, conversion factors, and properties of materials. W. E. Bush has written two chapters: Elements of the Vacuum System, and Vacuum Materials and Equipment. There is a chapter on Vacuum Gauges by K. M. Simpson. The final chapter on Leak-detection Instruments and Techniques includes among other topics complete descriptions of the vacuum analyzer and the helium leak detector developed for use in this project.

Now we have large and important industrial processes and whole new industries based on these vacuum techniques! All experimental scientists and engineers who must produce a high vacuum will find this a valuable reference volume. It is a bargain, too, considering the present high prices of books. W. W. WATSON

Seismicity of the Earth and Associated Phenomena; by B. GUTENBERG and C. F. RICHTER. Pp. x, 273; 34 figs. Princeton, New Jersey, 1949 (Princeton University Press, $10.00).—The title of this volume has appeared on several papers and abstracts published by the same authors within the past ten years. Their matured studies have led to results of large proportions and importance, and these results are now embodied in a book that will be welcomed by students of earth science. Considerably more than half of the pages, which measure 7.5 x 10.7 inches, are devoted to organized tabulation of shocks, numbering many hundreds, for which significant data are available. This part of the book is in

itself a highly valuable reference work. The first 100 pages are occupied with explanation and discussion, including not only text but also helpful maps and diagrams. A list of references to literature, alphabetized according to authors, requires 13 double-column pages. There are two indexes, one listing authors of reference literature, the other subjects treated in the present volume.

Materials and methods used in the study are clearly stated and explained in introductory sections. Magnitudes of earthquakes included range up to a maximum of 8½, on the scale developed from the suggestion by Richter, in classifying shallow shocks in southern California, that the number to express the magnitude of a shock be "the logarithm of the maximum trace amplitude expressed in thousandths of a millimeter with which the standard short-period torsion seismometer would register that earthquake at an epicentral distance of 100 kilometers." Later elaboration of the scale, including development of a nomogram, makes it applicable to all earthquakes that have been well recorded, whatever the type of instrument used. Magnitudes are correlated with amplitudes and periods of *P*, *PP*, and *S* in the records; this makes possible the inclusion of deep shocks, for which surface waves are small or practically absent. For the deep shocks, however, certain assumptions are involved regarding propagation of seismic energy in the interior of the earth, and accordingly some error in computed magnitudes is recognized.

Shocks are defined as shallow if depth of focus does not exceed 60 km.; intermediate if they fall within the limits 70 to 300 km.; and deep if the focus is below 300 km. By magnitude all shocks fall into five classes designated *a*, *b*, *c*, *d*, and *e*; those in *a* have the range 7¾-8½, those in *e* are below 5.3, and shocks in the other three categories have intermediate limits. For deep shocks the quality of determination ranges from *A* (very accurate) to *D* (poor); even for those classed as *A* the limits of error are: for location of epicenter 1°, for origin time 5 sec., for depth 30 km.

For convenience in reference the surface of the earth is divided into regions, boundaries of which are shown by an index map on modified Mollweide projection. Other maps, on the same projection, show: (1) shallow earthquakes of class *a* for the period 1904-1946, and of class *b* for 1918-1946; and (2) intermediate and deep-focus earthquakes, classes *a* and *b*, for 1904-1946. Of particular interest is the highly seismic circum-Pacific belt, which includes "a large majority of shallow shocks, a still larger fraction of intermediate shocks, and all the deep shocks in the restricted sense." Distribution of shocks in these three classes, in relation to island arcs and to the west coast of South America, commands attention of all students of tectonics. The vista of possibilities that lie in this kind of geo-

physical study is made more impressive by maps, chiefly of the East Indies and neighboring units, that depict earthquake data, gravity anomalies, volcanoes, and ocean depths. An impressive sketch map (Fig. 33) represents the "Pacific stable mass" framed by the belts of shallow, intermediate, and deep-focus earthquakes. Figure 34 represents each of the "continental stable masses" in relation to seismic belts.

Data from each major region of the earth are presented in considerable detail. General discussion is limited in scope, but brief sections deal with views on the constitution of the earth and on the mechanism of crustal movements. The largest contribution of the book lies in its presentation of basic data. In this respect it marks a significant advance in the pooling of information by the several disciplines engaged in the attack on fundamental problems of the earth's crust. CHESTER R. LONGWELL

Lehrbuch der Paläozoologie; by OSKAR KUHN. Pp. v, 326; 244 figs. Stuttgart, 1949 (E. Schweizerbart'sche Verlagsbuchhandlung, 28 marks unbound, 30 marks [$7.20] bound).—At first sight this handsome and richly illustrated new textbook will fascinate any paleontologist. With closer examination misgivings will arise and these may finally give way to dismay.

Kuhn belongs to the school of idealistic morphology of Naef and others, a school that is pre-evolutionary in source and outlook, as Kuhn recognizes, although this is denied by some other adherents. On principle, he rigidly orients this text around exposition of the "Urbild" ("archetype" of earlier days, "morphotype" of some modern students). With the single exception that he usually gives the geological age of the groups mentioned, the treatment is confined to diagnosis. The limitation is so stringent that it excludes not only faunal succession, phylogeny, paleoecology, paleobiology, or any mention of evolutionary, geological, or, indeed, paleontological principles, but also morphology itself. There is no systematic or, even on an elementary level, adequate exposition of the structure of any group of fossils.

The text is, then, essentially a series of summary diagnoses of each phylum ("Kreis") known as fossils and of lesser groups, usually carried down to orders, with some sporadic notice of particular genera but practically no mention of families or other intermediate categories. These diagnoses, as such, are generally adequate and useful. It is inevitable in so extensive a compilation that errors of detail have crept in, although they seem in some places to be more numerous than is strictly necessary.

The illustrative material is remarkably extensive and makes a useful collection of figures. Many of the 244 numbered figures are

multiple, so that the number of separate illustrations may be over a thousand. Yet even this truly outstanding feature of the book must be viewed with some reservations, because the figures are very uneven in quality and are commonly drawn from secondary sources, with reference to the true source omitted or incorrect. Such a criticism requires some documentation. Figure 213, captioned "Skelett eines oberjurassischen Stegosauriers . . . Nach ROMER," is a direct, although reduced and somewhat blurred, copy of a figure published by Barnum Brown in 1908 and not reproduced in any work by Romer known to this reviewer. Moreover, as was clearly stated by Brown, the animal is late Cretaceous, not late Jurassic, in age and it is an ankylosaur, not a stegosaur. The single example must suffice here, but it is not an isolated instance.

A book should be judged within the framework of its author's own aims. This book is intended as a text on diagnosis of major groups of fossil animals for German-speaking students and as such it is reasonably successful, with certain reservations as already suggested. Using due caution, American paleontologists may find it occasionally helpful as a broad work of organization and reference.

G. G. SIMPSON

Die Festigkeitserscheinungen der Kristalle; by H. TERTSCH. Pp. vii, 310; 219 figs. Vienna, 1949 (Springer Verlag, $9.60). Commenting that mineralogists treat various branches of physical crystallography with varying degrees of thoroughness, Tertsch sets out in this book to help remedy the unbalance by presenting a careful review of certain solid properties of crystals. He covers four main subjects, namely cleavage (46 pp.), plasticity (214 pp.), hardness (86 pp.), and percussion and pressure figures (25 pp.). Each of these subjects is introduced by an historical and general section, followed by appropriate sections on qualitative and quantitative observations, and finally by theoretical interpretations.

No attempt is made to introduce new material, but rather to collect and review what is already available; the result is exceedingly satisfactory. As stated by Tertsch himself, summaries of knowledge usually introduce many new questions not previously considered; this book is no exception. To review a problem intelligently is nearly always the first step toward a further, successful attack upon it.

As a text or as a reference, this book is lucid and thorough enough to serve both students and research workers. The 12-page index, and the 15-page bibliography (317 references) are well arranged to promote both purposes. The cross-indexing of secondary authors in the bibliography is particularly commended. The whole book is a good job, well done.

HORACE WINCHELL

Studies on Triassic Fishes, II. *Australosomus and Birgeria*; by EIGIL NIELSEN. Meddelelser om Grønland, Band 146, nr. 1; 82 figs., 20 plates. København, 1949 (25,00 Kr.).—The second portion of Dr. Nielsen's monograph of the Triassic fishes collected by the Danish East Greenland Expeditions under Dr. Lauge Koch between 1932 and 1938 deals with two genera of somewhat advanced chondrostean fishes from the Eotriassic, mainly of the Kap Stosch area. *Australosomus kochi* (Stensiö) was a fish averaging 12 to 15 cm. long belonging to the Pholidopleuridae, a family derived from the primitive paleonisciform fishes of the Paleozoic which had evolved toward, but never attained holostean structure. *Birgeria groenlandica* Stensiö, known from both small (9-21 cm.) and larger (53-84 cm.) specimens, was a predaceous fish with an enormously enlarged mouth and a body almost naked of scales, and is close to the ancestry of the living paddle fish and sturgeons. Nielsen exhaustively describes every part of the skeletal anatomy of these fishes on the basis of 235 specimens of the former and 109 of the latter. The skull and endrocranial cavities of *Australosomus* are described and figured from wax models constructed from serial sections ground at intervals of 100 (in critical regions 50) microns.

In passing, a number of general remarks are made concerning bony fish evolution. Nielsen repeatedly points out resemblances between primitive Actinopterygians and Acanthodians, and suggests the origin of the bony fishes from the latter group. Westoll's hypothesis that the position of the pectoral fin in bony fish shifted from horizontal to vertical in correlation with loss of the heterocercal tail is questioned, as both *Australosomus* (with horizontal pectoral and nearly homocercal tail) and *Birgeria* (with vertical pectoral and unreduced heterocercal caudal) present contrary combinations.

The question of priority of *Xenesthes* Jordan over *Birgeria* Stensiö is passed over in silence; this is a matter, however, for action by the International Commission on Zoological Nomenclature rather than continued individual discussion.

Dr. Nielsen is furnishing extremely useful basic data for the phylogeny of the bony fishes and a valuable set of types for anatomical comparison. The excellent plates, numerous well labeled figures, orderly presentation, and full summaries so characteristic of publications of the Scandinavian paleontologists leave little to be desired. It is to be hoped that further reports on this fauna will appear at shorter intervals than intervened between parts I and II.

JOSEPH T. GREGORY

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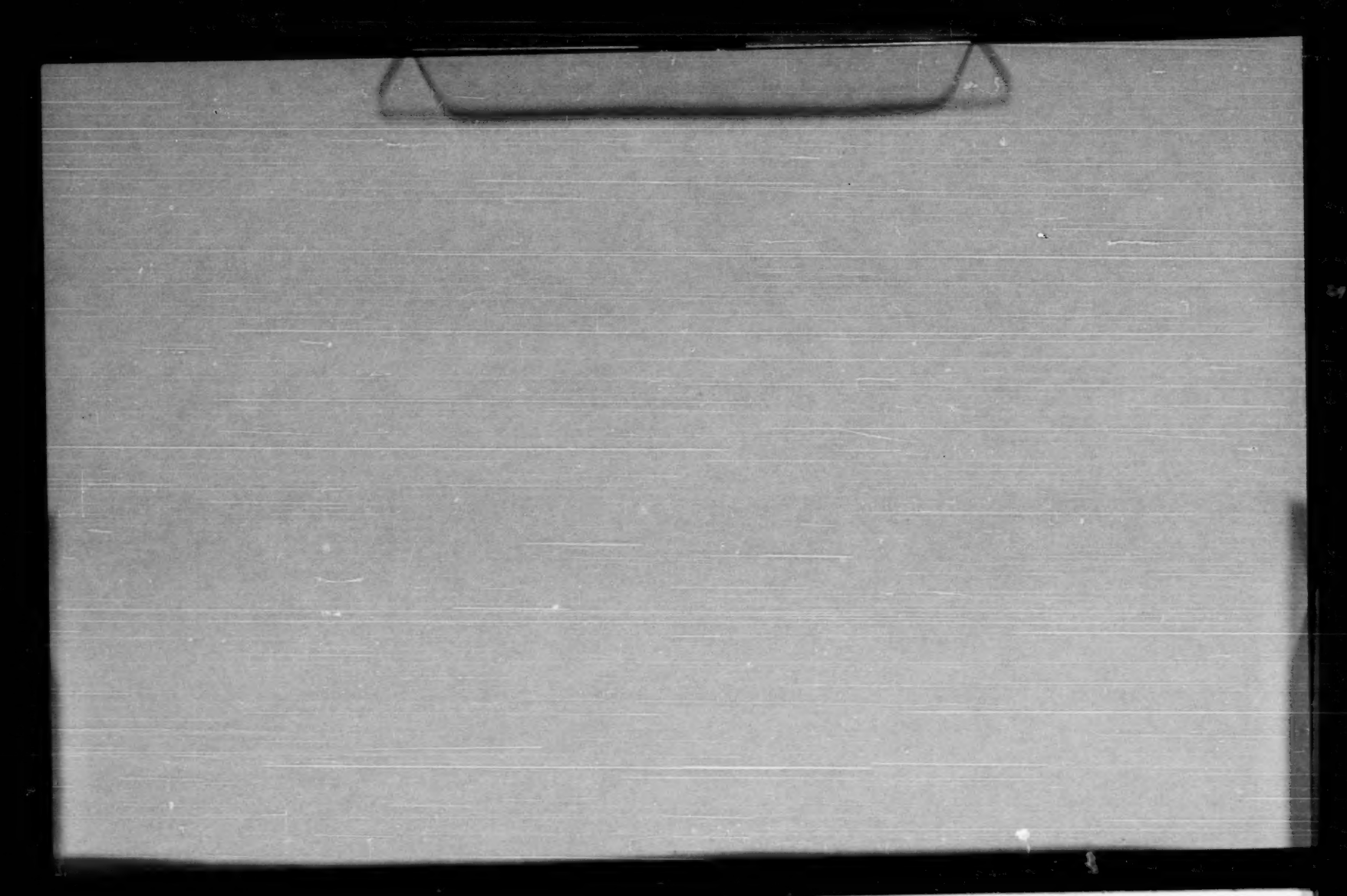

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